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PROGRESS IN RADIATION IMMUNE THERMIONIC INTEGRATED CIRCUITS

Compiled by

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ABSTRACT

This report describes the results of a program directed at evaluating the thermionic integrated circuit (TIC) technology for applicability to military systems. Previous programs under the sponsorship of the Department of Energy, Office of Basic Energy Sciences, have developed an initial TIC technology base and demonstrated operation in high-temperature and high-radiation environments. The program described in this report has two parts: (1) a technical portion in which experiments and analyses were conducted to refine perceptions of near-term as well as ultimate performance levels of the TIC technology and (2) an applications portion in which the technical conclusions were to be evaluated against potential military applications. This report draws several conclusions that strongly suggest that (1) useful radiation-hard/high-temperature operable integrated circuits can be developed using the TIC technology; (2) because of their ability to survive and operate in hostile environments, a variety of potential military applications have been projected for this technology; and (3) based on the above two conclusions, an aggressive TIC development program should be initiated to provide the designers of future systems with integrated circuits and devices with the unique features of the TICs.

I. SUMMARY

A. Background

The nature, mission, tactics, and capability of military systems derive from available technology. In the last 25 years, the trend has been toward "smarter" weapons systems with more built-in functionality and capability for autonomous action and with the ability to communicate at higher rates and process more information. This trend, of course, has derived from progress in semiconductor and integrated circuit technology, which has provided increasing miniaturization and lower-power and higher-speed electronic components and integrated circuits. The resultant increase in system capability has been dramatic. Modern weapons systems such as cruise missiles and satellite systems would be virtually impossible without solid-state device technology. Unfortunately, one of the penalties in the solid-state evolution has been an increasing susceptibility to nuclear weapon and space radiation effects.

Thermionic integrated circuits (TICs), on the other hand, derive from vacuum tube technology. They are manufactured with the use of photolithographic and fabrication techniques developed for conventional integrated circuits, and they yield thin-film microminiature devices produced simultaneously by the thousands on the same substrate in the form of integrated circuits. Figures I-1, -2, and -3 depict current TIC device structures and fabrication process sequence. The TIC technology has been developed at Los Alamos National Laboratory principally under the sponsorship of the Department of Energy, Office of Basic Energy Sciences, for application in high-temperature environments. TIC devices and circuits have shown a high degree of resistance to nuclear radiation and high-temperature environments.

The program reported on in this document was initiated under DARPA sponsorship to evaluate the TIC technology for its applicability to future military systems.

Fig. I-1. Vertical TIC gain device.

Fig. I-2. Coplanar TIC gain device.

THIN FILM DEPOSITION - CIRCUIT SIDE

PATTERN DEFINITION - RF PLASMA ETCHED

Ti - Mo REMOVED FROM CATHODE BY CHEMICAL ETCH

CATHODE COATING APPLIED AND DEFINED PHOTOGRAPHICALLY

Fig. I-3. TIC metalization and photolithography processes.

B. Objective

As stated in the March 1982 proposal to DARPA,* "The objective of the 1-year program is to verify the applicability of the TIC technology for military radiation-hardened applications. The key concepts here are verification and applications; the program is directed at enhancing present estimates of performance and refining perceptions of those applications for which the technology appears most appropriate and derives the largest benefits. The technical issues to be addressed are

- o device bandwidth/speed,
- o power requirements,
- o level of integration,
- o vulnerability, and
- o life and reliability."

Additional guidance from the sponsor suggests the importance of the applications portion of this study and that the space reactor environment in particular should be carefully evaluated.

The experiments and analyses performed on these five technical issues are described in detail in Sections II-VI.

C. Approach

It was recognized from the outset that the level of funding for this project was inadequate to answer definitively the many questions regarding both TIC technology and potential applications and to perform the required in-depth experiments or analyses. Therefore, since the general rationale for this project is to evaluate applicability of TIC technology to weapons systems and concurrently to develop insights for guiding future TIC development programs, broad discussions with both governmental agencies and industry (Section VIII.B) have been initiated, and based on those discussions, varying emphasis has been given to the types and depth of the technical evaluations performed. Based on sponsor guidance suggesting the importance of applications, a small amount of the DARPA program funding augmented by Los Alamos funding in an approximately equal amount has been set aside for a contract with one of several companies

*Since there was a delay of nearly a year between the funding approval at DARPA and receipt of funds at Los Alamos, portions of the results described in the following sections were performed between March 82 and February 83 in anticipation of and for the DARPA-sponsored program.

to perform an independent evaluation of the TIC technology vs applications. After the competitive RFP process, R & D Associates has been selected to carry out this analysis. Also, since beam weapons represent an important possible threat in the future, Dr. George Messenger has been retained by Los Alamos as a consultant to evaluate and report upon the threat posed to electronics by beam weapons and to evaluate the TIC technology as related to that emerging weapons concept.

The major portion of this report (Sections II-VII) contains results of numerous calculations and experiments that have been conducted as part of the DARPA-sponsored project to provide a sound basis for making future programmatic decisions and suggests directions for future programs based on technological and applications insights developed to date.

D. Synopsis of Conclusions

1. Applications (Discussions/Conclusions). There is growing industrial and governmental interest in the TIC technology as evidenced by the list of discussions conducted to date (Section VIII.B). It should be noted that a majority of the discussions with industry have been initiated by industry. A few of the possible applications discussed to date include the following:

- o Launch control for hard mobile missile - BMO
- o Selective hardening of satellites - Hughes Aircraft, Air Force Space Command
- o Hardened RPVs (remotely piloted vehicles) and battlefield sensors - Air Force Systems Command, Hughes Aircraft, Mission Research Corp.
- o Reactor safety, military, and nonmilitary - GA Technologies*
- o Arming, fuzing, and terminal guidance - Sandia National Laboratories, Naval Weapons Systems Center
- o Hardened controls/power devices for both space and terrestrial reactors - JPL, GA Technologies, Lockheed, Martin Marietta, General Electric
- o Hardened C³I - Defense Communications Agency, Strategic Air Command, JPL

*Formerly General Atomic.

- o Jet engine instrumentation/control ("fly by wire") - Strategic Air Command, a jet engine manufacturer*

A general conclusion from these discussions is that TICs can affect future weapons systems by increasing the tolerance of their electronic systems to environments in which the electronics must operate and survive. That is to say that systems and, therefore, military missions are designed to accommodate the limitations of existing technology. The TIC technology is receiving its best response from personnel working on new systems at the conceptual stage. For example, SP-100 and hard mobile missiles represent important applications for which total dose survivability well beyond that of current technologies would be extremely desirable. In many cases, the definition of the mission of a particular system would be expanded based on improved hardening, e.g., ballistic missile terminal guidance. In still other cases, new threats are emerging (e.g., beam weapons) as are new scenarios such as flexible response during nuclear conflict, for which improved radiation hardness may be required.

Based on the discussions held to date, several conclusions regarding technological issues may be drawn.

- o Use of TICs in concert with silicon or gallium arsenide integrated circuitry is universally recommended as the appropriate method for utilizing the TIC technology (Figs. I-4 and -5).
- o Many applications appear for TICs at the small- or medium-scale integration levels (20-1000 devices).
- o Because of the selected use of this technology, powers of 2 mW per device (as projected later in this report) are acceptable, even for satellite systems.
- o Many potential applications exist at the speed/bandwidth projected.
- o Concern about electromagnetic pulse (EMP) is large; and in a follow-on program, thorough EMP testing should be undertaken.
- o The high-temperature capability of these devices could be advantageous to a number of military systems.
- o Power devices should be investigated.

*The company is not named because it is in the process of contracting with Los Alamos to evaluate this application in more detail.

Fig. I-4. Hybrid approach using TICs and semiconductors.

Fig. I-5. Parallel approach using TICs and semiconductors. TICs would be activated upon failure of the semiconductor system.

Concern for timeliness in availability of this technology has been expressed by several parties, particularly with regard to validation for military systems.

Although the TIC technology is new to most of the personnel involved in recent discussions, the level of interest has been high in spite of the novelty. This strongly suggests the perceived benefit of a technology such as TICs that complements silicon and GaAs integrated circuits by providing additional radiation hardness and high-temperature operability.

2. Technical Accomplishments. The following is a list of technical milestones accomplished during this program.

- o The first fully integrated thermionic circuit has been designed and tested, demonstrating the feasibility of the TIC concept (Section III).*
- o Device speed has been analyzed, and it has been found that devices with gain bandwidths of a few tens to a couple of hundred megahertz are possible with existing technology (depending on current density drawn from the cathode) and that gain bandwidth products approaching a gigahertz may be possible with enhanced processing (Section V).
- o Theory and experiment have been correlated and have shown that with a properly designed package at a level of integration of 1000 devices/in², required heater powers will be as low as 2 mW/device. At 10,000 devices/in², this will drop to 0.2 mW/device (Section IV).
- o Fabrication process improvements have been developed and verified so that resistive leakage and spurious emissions have been reduced to a level in all devices tested where cathode current is at least three orders of magnitude larger than parasitic emission and resistive leakage currents. This suggests that no problem should be encountered at levels of integration currently envisioned (Section III).
- o The transient radiation (γ) response of a single flip-flop has been analyzed. It has been predicted theoretically and confirmed experimentally that the substrate of present-day devices is the major contributor to the transient radiation response. For a 30-mil-thick substrate and the current flip-flop layout, the analysis predicts an

*Both DARPA and DOE funding were used in accomplishing these tasks.

upset level of 2×10^9 rad(Si)/s. However, an improved substrate and circuit layout is projected to achieve 4×10^{11} rad(Si)/s for upset levels, with levels greater than 10^{12} rad(Si)/s perhaps being possible in the long term (Section II).

- o Based on the integrated circuit designed and demonstrated and the process improvements achieved* and on computer analyses, TICs at integration levels of 1000 devices/in² or better (perhaps up to 10,000) appear likely in the near term (Section III).
- o Under sponsorship of a major computer manufacturer, experiments aimed at determining factors influencing lifetime have been initiated (aimed at a product of unique interest to that corporation) (Section VII).

E. Programmatic Recommendations

From the discussions with industry and government agencies to date, it is evident that there is a need for a technology with radiation-hardened characteristics such as the TICs to complement the capabilities/limitations of silicon and gallium arsenide. A major recommendation of this program, therefore, is to proceed with a long-term program. However, such a program should include the continued evaluation of applications and discussions with possible users so that (1) the user community can evaluate applicability and timing of the TIC technology to respond to the needs of their particular systems and (2) the TIC technology program can be effectively directed at the requirements of important applications.

From a technical point of view, many specific recommendations have emerged from the current program.

Vulnerability

- o Improved substrates must be developed to improve transient gamma and charged particle response.
- o EMP tests must be conducted.
- o Continuous radiation tests must be conducted throughout the program to expedite validation and fielding of TIC circuitry.

*Both DARPA and DOE funding were used in accomplishing these tasks.

- o More thorough total dose tests must be conducted to determine failure levels.

Level of Integration

- o A major investment in circuit technology is required, including investigation of ways to take advantage of and effectively utilize electrostatic interactions.
- o CAD tools including 3D Laplace and variable mesh Poisson codes must be developed and current state-of-the-art CAD mask-making and circuit analysis tools must be modified to support TIC development.
- o Advanced device structures including current sources and high offset devices should be investigated.
- o Perhaps most important, an investment must be made in statistical data taking, characterizing many devices on many substrates so that design rules can be derived for circuitry producible at high yields (developing this data is more difficult in TIC technology than it is in conventional solid-state integrated circuits because the vacuum package isolates the devices, making them difficult or impossible to probe).
- o Improvements in processing must be investigated including continued evolution of lower leakage, lower spurious emission processes, as well as finer lithography.
- o Improved cathode structures should be investigated, including those that yield higher current density and/or finer geometry as well as those with enhanced tolerance to gases that may contaminate the vacuum.
- o Additional fabrication techniques must be investigated, including the development of crossovers, resistors, and capacitors.
- o Near-term simple functional circuits must be designed and tested, starting with an analog circuit (operational amplifier) and simple digital circuits (gates and flip-flops). These simple circuits must then be refined to begin the evolution toward analog-to-digital converters, registers, arithmetic logic units, etc.

Heater Power

- o Materials for reflective coatings must be investigated, and methods for applying them to the package must be developed.

- o Reflective coatings directly on the substrate must be investigated.

Device Speed/Bandwidth

- o Tests of current density vs lifetime on cathodes must be continued.
- o Advanced, higher-current density cathodes should be investigated.
- o Processes yielding finer lithography should be investigated.
- o "Grooved" substrates to reduce grid-to-cathode capacitance should be developed.

Life and Reliability

- o Thorough life and reliability tests should be initiated.
- o Degradation mechanisms in cathodes should be investigated.
- o Improved packaging, including "gettering" techniques to minimize gas evolution into the vacuum, and more rugged pin seals and welds should be investigated.

Package

- o Practical and useful TIC packages must be designed and developed with appropriate thermal characteristics and with the ability to withstand high temperatures, shock, and vibration.

Power Devices

- o Power device structures should be designed and tested.

The following sections describe in detail the technical basis for these conclusions and preliminary analyses and experiments performed under the current DARPA program (in concert with DOE-sponsored research), which underlies the recommendations made above.

II. VULNERABILITY*

A. Statement of Work from Proposal (March 1982)

"Single devices have been tested to the following levels: 1×10^{17} neutrons/cm²; 2.5×10^8 rad(Si); 1.4×10^{16} neutrons/cm²s; and 1.2×10^7

*Because there was a delay of nearly a year between the funding approval at DARPA and receipt of funds at Los Alamos, portions of the results described in the following sections were performed between March 82 and February 83 in anticipation of and for the DARPA-sponsored program.

rad(Si)/s. During these tests, negligible change of device dc characteristics was observed. These tests, it must be emphasized, were 'quick and dirty' tests to verify feasibility of the technology for radiation-hardened applications. However, even though the results of these tests were limited by the capability of the particular reactor used (100-kW TRIGA), in all cases except gamma flux, the resultant levels exceed current silicon performance levels. In the gamma rate case, tests with earlier vacuum tubes such as NUVISTORS have shown capabilities exceeding 10^{11} rad(Si)/s.

"Another important parameter in determining the effectiveness of a particular technology in a high-radiation environment is recovery time; that is the time required for a device to return to acceptable operation after an upset.

"Individual devices and simple circuits will be radiation tested on a continuing basis during the second half of the 1-year program. Since it is expected that gamma flux is of most fundamental importance for envisioned military applications, device response as a function of gamma flux and recovery time from upset will be measured. No total dose tests beyond those previously conducted are currently planned for the 1-year program."

B. Temperature Tests

TIC devices have been operated successfully in high-temperature environments. A device has been operated continuously at 500°C ambient temperature for 13,000 hours with no degradation in device characteristics. After 13,000 hours a pin seal failed, allowing air to leak into the package. In addition, a Hartley oscillator was operated successfully in a 500°C environment. These tests were performed before the DARPA-sponsored program; the results are summarized for reference.

C. Radiation Test Summary

A number of tests have been performed on single TIC devices. The first tests were performed at the University of Arizona (U of A) in July 1979 and are included here for completeness. Next, as part of the current DARPA program, a series of gamma dose rate tests were performed at the Air Force Weapons Laboratory (AFWL) Febetron facility in Albuquerque, New Mexico. Finally, devices were tested in the proton beam at the Weapons Neutron Research (WNR) facility

at Los Alamos. Devices have been tested to the levels shown in Table II-1 with no observable change in characteristics.

TABLE II-1
SINGLE-DEVICE RADIATION TESTS

<u>Total Dose</u>	<u>Dose Rate</u>	<u>Pulse Duration</u>	<u>Type</u>	<u>Facility</u>
$1 \times 10^{17} \text{ n/cm}^2$			neutron	U of A TRIGA, 100 kW, continuous
$2.5 \times 10^8 \text{ rad(Si)}$			gamma	U of A TRIGA, 100 kW, continuous
	$1.4 \times 10^{16} \text{ n/cm}^2\text{s}$	20 ms	neutron	U of A TRIGA, 750 MW, pulsed
899 rad(Si)/pulse	$4.5 \times 10^{10} \text{ rad(Si)/s}$	20 ns	gamma	AFWL Febetron
960 rad(Si)/pulse ^a	$2 \times 10^8 \text{ rad(Si)/s}^b$	4.8 μs	proton	WNR

^a $(3 \times 10^{10} \text{ protons/cm}^2 \text{ pulse})$.

^b $(6.2 \times 10^{15} \text{ protons/cm}^2\text{s})$.

The U of A tests were performed with a TRIGA reactor from Gulf General Atomic, capable of 100-kW continuous and 750-MW pulsed operation. During these tests, the devices were active and were continuously monitored for changes in characteristics. The total dose tests produced no effect on the device characteristics. When the reactor was pulsed at 750 MW, the triode characteristics showed an instantaneous shift during the pulse with an almost immediate recovery.

Tests with the AFWL Febetron show that the TIC devices with their current structure show a response for gamma dose rates above 10^8 rad(Si)/s . As nearly as can be determined, this response lasts only for the length of the gamma pulse. At dose rates as high as $4.5 \times 10^{10} \text{ rad(Si)/s}$, the devices recover quickly and show no permanent effects. Both tests and analyses indicate that the transient gamma response is dominated by the sapphire substrate. An improved substrate structure, already tested in a preliminary form, is proposed that would reduce the gamma dose rate response by orders of magnitude.

Devices were tested in the 800-MeV proton beam at WNR to a level of 2×10^8 rad(Si)/s. At this level, the devices showed a response, but again, this response lasted only for the duration of the pulse.

In addition, a TIC flip-flop was tested in the proton beam. The pulse width of the beam was adjusted until the flip-flop was at the threshold of upset. It was found that the flip-flop's upset threshold is 28 rad(Si) delivered in 200 ns, a rate of 1.4×10^8 rad(Si)/s. [The calculated $\dot{\gamma}$ upset level of this flip-flop is 2.2×10^9 rad(Si)/s for 20 ns, or a total dose of 45 rad(Si).]

The proton upset mechanism should be somewhat different than the $\dot{\gamma}$ mechanism. The protons impart less energy to the electrons, and the electron motion is much less directional. The number of ejected electrons will be lower, but the number of electron-hole pairs generated and the associated conductivity effects will be greater for protons. The substrate improvements geared to improve the $\dot{\gamma}$ tolerance, particularly the measures to reduce the radiation-induced conductivity, should also improve the proton dose rate tolerance. However, additional measurements must be made to determine the proton-induced conductivity effects in different substrate materials.

D. Gamma Dose Rate Response

Because the total dose tests produced no observable degradation in the TIC characteristics and because the initial dose rate tests indicated that the TIC devices showed a response for gamma dose rates above 10^8 rad(Si)/s, the effort during this program was concentrated on measuring and understanding dose rate response. Specifically, the goals were to

- o Gain an understanding of the dose rate response mechanisms by analyzing a number of device and electrode configurations and then conducting measurements to verify the analyses.
- o Design structures that would have reduced responses and then verify that the responses are indeed reduced.
- o Determine how TIC device response affects circuit performance by calculating and measuring the effect of dose rate on a logic inverter and a flip-flop.
- o Project the dose rate tolerance of the flip-flop when improved substrate and device structures are used.

1. Analysis of Mechanisms. Two important effects that can contribute to the dose rate response of the TICs are photon-electron interactions and radiation-induced conductivity. How these mechanisms affect TIC circuit performance is analyzed in Sections a and b below.

a. Photon Interactions. The photon energies produced by the AFWL Febe-
tron are in the 1-MeV range. In this energy range, the dominant interaction mechanism is Compton scattering of photons by electrons. Compton scattering imparts energy to the electrons; the average motion of these electrons is in the direction of the incident photons. Thus, there is a net transport of negative charge in the direction of the photons. It is this motion of charge that produces the dose rate response.

The number of photons removed from the incident beam, Δp , in distance Δx is

$$\Delta p = p\mu\Delta x \quad \text{photons/cm}^2, \quad (\text{II-1})$$

where

$$\begin{aligned} \Delta p &= \text{photons removed/cm}^2, \\ p &= \text{incident photons/cm}^2, \\ \mu &= \text{photon absorption coefficient (cross section), cm}^{-1}, \text{ and} \\ \Delta x &= \text{distance traversed, cm.} \end{aligned}$$

For a thin sample of material of thickness x (μx less than about 0.1), the total number of photons removed from the sample is

$$\Delta p = p\mu x \quad \text{photons/cm}^2. \quad (\text{II-2})$$

For a thin sample, approximately one electron is ejected for each captured photon. Then the number of ejected electrons is

$$N_e = p\mu x \quad \text{electrons/cm}^2, \quad (\text{II-3})$$

and the ejected charge is

$$q = e p\mu x \quad \text{C/cm}^2, \quad (\text{II-4})$$

where

$$e = 1.602 \times 10^{-19} \text{ C} . \quad (\text{II-5})$$

Gamma radiation levels are generally expressed in rads (1 rad = 100 ergs/gram absorbed). The energy absorbed by the material is

$$E_a = \mu_p E_p x A \quad \text{eV} \quad (\text{II-6})$$

or

$$E_a/m = e p (\mu/\rho) E_p \times 10^7 \quad \text{ergs/gram}, \quad (\text{II-7})$$

where

E_p = energy of incident photons, eV,
 A = area of material, cm^2 ,
 m = mass of material, grams, and
 ρ = density of material, grams/cm^3 . Then

$$p = \frac{10^{-5}}{e E_p (\mu/\rho)} \gamma \quad \text{photons/cm}^2 , \quad (\text{II-8})$$

where γ = rads. If units of rads are selected for the purposes of comparison, with material 1 being the reference (e.g., silicon) and material 2 being the material under test, then the ejected charge is

$$q = \frac{\mu_2 x_2 \gamma_1}{E_p (\mu_1/\rho_1)} 10^{-5} \quad \text{C/cm}^2 , \quad (\text{II-9})$$

and the current density is

$$J = \frac{\mu_2 \times_2 \dot{\gamma}_1}{E_p(\mu_1/\rho_1)} 10^{-5} \quad \text{A/cm}^2, \quad (\text{II-10})$$

$\dot{\gamma}_1$ = dose rate, rad/s

Table II-2 gives several radiation parameters for some of the materials of interest. In the calculations that follow, for purposes of comparison with current silicon IC technology, $\gamma_1 = \text{rad}(\text{Si})$ and $\dot{\gamma}_1 = \text{rad}(\text{Si})/\text{s}$.

TABLE II-2

RADIATION PARAMETERS FOR SOME MATERIALS OF INTEREST FOR THE TICs

Material	ρ (g/cm ³)	$E_p = 0.6 \times 10^6 \text{ eV}$			$E_p = 10^6 \text{ eV}$		
		$p = 12.92 \times 10^8 \text{ } \gamma \text{ photons/cm}^2$			$p = 9.83 \times 10^8 \text{ } \gamma \text{ photons/cm}^2$		
		μ	Electron Range (cm)	q/xR (C/cm ²)/cm rad	u	Electron Range (cm)	q/xR (C/cm ²)/cm rad
		(cm ⁻¹)			(cm ⁻¹)		
Al	2.70	0.210	0.0822	43.5×10^{-12}	0.166	0.160	26.1×10^{-12}
Si	2.33	0.188	0.0984	38.9×10^{-12}	0.148	0.192	23.3×10^{-12}
Ti	4.5	0.339	0.0470	70.2×10^{-12}	0.263	0.0914	41.4×10^{-12}
Ni	8.9	0.682	0.0247	141×10^{-12}	0.548	0.0480	86.3×10^{-12}
Mo	10.2	0.794	0.0198	164×10^{-12}	0.593	0.0385	93.3×10^{-12}
W	19.3	2.03	0.00962	420×10^{-12}	1.26	0.0187	199×10^{-12}
Pt	21.45	2.40	0.00859	497×10^{-12}	1.45	0.0167	228×10^{-12}
Pb	11.34	1.35	0.0161	279×10^{-12}	0.797	0.0313	126×10^{-12}
Al ₂ O ₃	3.965	0.314	0.0570	65.0×10^{-12}	0.248	0.111	39.0×10^{-12}

Normally, the incident photon beam has some energy distribution, and as can be seen from Table II-2, μ is a function of energy. In general, accounting for the energy distribution would require numerical solutions necessarily done on a computer. In order to provide an approximate analytic solution, the above

equations will be applied assuming a single photon energy. Normally, the photon energy used will be the average energy of the photon beam (about 1 MeV for the AFWL Febetron).

When more accuracy was required, a computer code* for the solution of coupled electron/photon transport through multimaterial configurations was used. In addition, the code was used to verify that the above equations provide reasonable approximations, at least for thin materials. Figure II-1 compares Eq. (II-3) with the results of the computer code for 1-MeV incident photons. The agreement is good for sapphire less than 10 mils thick. Above 10 mils, Eq. (II-3) gives a pessimistic result.

b. Radiation-Induced Conductivity. Insulating materials can undergo an increase in electrical conductivity when subjected to ionizing radiation.¹ A large enough change in the conductivity of a TIC substrate could also affect the radiation tolerance of the TIC.

Radiation-induced conductivity (RIC) is strongly influenced by temperature and dose rate. In addition, the RIC of sapphire can be altered drastically by doping or by changing the crystal structure. Figure II-2 shows data from Refs. 1 and 2 for two undoped samples of sapphire, samples doped with 0.0004 wt% Cr_2O_3 and 0.03 wt% Cr_2O_3 , and a neutron-irradiated sample, all at 1000 K. The RIC varies by more than three orders of magnitude. Thus, the use of doped or neutron-irradiated sapphire or polycrystalline alumina for the TIC substrate can greatly reduce the RIC. However, the data shown in Fig. II-2 are for radiation levels only up to 6.6×10^4 rad/s. RIC measurements need to be made for much higher radiation levels.

It was shown in the previous section that the charge ejected by photons from a thin material is proportional to the thickness of the material. However, the current or charge induced in an insulator by an electrode above a ground plane will be inversely proportional to the insulator thickness. Then, if the insulator is made thinner, there will be a point at which the current in the insulator caused by RIC is equal to the current caused by photon-ejected electrons.

*The code is a version of CYLTRAN, developed at Sandia National Laboratories and modified and extended at Los Alamos.

Fig. II-1. Electrons ejected from sapphire per incident 1-MeV photon.

Fig. II-2. Sapphire conductivity as a function of radiation dose rate.

For a node with a high impedance to ground, the change in node voltage caused by RIC in a short period of time Δt is

$$\Delta v_{\sigma} = - \frac{V \Delta t}{RC} = - \frac{V \Delta t \sigma A}{\ell C} , \quad (\text{II-11})$$

where V is the node voltage, σ is the conductivity of the insulator, C is the node capacitance, and A is the electrode area. An approximate relation between RIC and dose rate¹ is

$$\sigma = K \dot{\gamma}^{\delta} , \quad (\text{II-12})$$

where typically, $\delta \leq 1$. Figure II-2 gives values of K and δ calculated from the data in Ref. 1.

The change in node voltage caused by electrons ejected by 1-MeV photons for sapphire is

$$\Delta v_p = \frac{Q_p}{C} = \frac{39 \times 10^{-12} \ell \gamma A}{2C} , \quad (\text{II-13})$$

where the factor of 2 in the denominator appears because the ground plane supplies about half of the replacement electrons.

The two effects are about equal when $\Delta v_p = -\Delta v_{\sigma}$ or

$$V = \frac{19.5 \times 10^{-12} \ell^2 \dot{\gamma}}{\sigma} . \quad (\text{II-14})$$

If σ_o is known for some radiation level γ_o , but the radiation level of interest is

$$\dot{\gamma} = \dot{\gamma}_o + \dot{\gamma}_1 , \quad (\text{II-15})$$

then

$$\sigma = K(\dot{\gamma}_o + \dot{\gamma}_1)^{\delta} = \sigma_o \left(1 + \frac{\dot{\gamma}_1}{\dot{\gamma}_o} \right)^{\delta} . \quad (\text{II-16})$$

Since $\delta \leq 1$, a conservative expression for the RIC is

$$\sigma = \sigma_o \left(1 + \frac{\dot{\gamma}_1}{\dot{\gamma}_o} \right) \quad (\text{II-17})$$

and

$$V = \frac{19.5 \times 10^{-12} \ell^2 \dot{\gamma}_o^2}{\sigma_o} . \quad (\text{II-18})$$

This equation can be used to estimate either the maximum voltage at a high impedance node for a given thickness or the minimum thickness for a given voltage, for which RIC effects become as important as photon-ejected charge. What is required is an RIC value, σ_o , near the radiation level of interest.

2. Initial $\dot{\gamma}$ Tests. The initial $\dot{\gamma}$ tests were conducted on TIC gain devices in both metal and glass envelopes. In addition, tests were conducted on a dummy package (package and pins but without triode and wire bonds) in order to separate package effects from device effects. Figure II-3 shows the grid-cathode structure of the gain device; the two triodes are connected in parallel. The triode package configuration is shown in Fig. II-4. A schematic of the test fixture used is shown in Fig. II-5.

The first tests were conducted with the tube envelope touching the Febe-tron faceplate and with the bond pads, bond wires, and package pins exposed to the radiation. The measured radiation levels are shown in Table II-3.

TABLE II-3

DOSE RATES AT PACKAGE AND SURFACE OF DEVICE

	Total Dose [rad(Si)]	Dose Rate [rad(Si)/s]
At envelope surface	2278	1.1×10^{11}
At plane of cathode	899	4.5×10^{10}

	Total area (sq mils)
Sapphire	442 000
Grid	16 400 (2200 active)
Cathode	18 400 (3000 active)
Shield	122 000

Pt surface area (bond pads)
2000 sq mils on each leg.
Balance of metal is
Ti surface.

Fig. II-3. Dual triode TIC gain device for radiation tests. Substrate containing grid and cathode structures.

Anodes 0.010 x 0.125
x 0.250 in. Ti on Ta
support wire

0.25-in.-diam. Ta
supports with 0.005-
x 0.040- x 0.25-in.
Pt straps to substrate

0.040-in.-diam. Mo pins
2.220 in. above ceramic

Sapphire ~2 cm above
bottom of Kovar ring

0.005-in. Pt grid
and cathode wires

Fig. II-4. Radiation test triode package configuration. Pin connections during test: 1--not used; 2--cathode through 1 k Ω ; 3--shield through 1 k Ω ; 4--not used; 5--heater ground; 6--heater +33 V; 7--not used; 8--not used; 9--shield pin floating; 10--grid through 1 k Ω ; 11--anode to +60 V.

Fig. II-5. Circuit for triode radiation tests.

The response of the dummy glass package is shown in Fig. II-6, while the response of the dual triode in a glass package is shown in Fig. II-7. A dual triode in a metal package was also tested with the results shown in Fig. II-8. The package with its pins is a substantial contributor to the total response, while the total response does not appear to depend on whether the package is glass or metal. The peak measured currents and total displaced charges are shown in Table II-4.

TABLE II-4

PEAK CURRENT AND CHARGE DISPLACED FOR PACKAGE AND PACKAGE PLUS DEVICE

	Grid		Cathode		Shield	
	<u>I(mA)</u>	<u>Q(pC)</u>	<u>I(mA)</u>	<u>Q(pC)</u>	<u>I(mA)</u>	<u>Q(pC)</u>
Empty Envelope	6	600	3	360	4	440
Dual Triode (Glass)	8	800	7	840	13	1320
Dual Triode (Metal)	8	1040	7.5	1000	10	1700

The time constant of the response is about 80 ns. The capacitance of the coax between the 1-k Ω sense resistor and line driver is about 50 pF, giving a time constant of about 50 ns. It is then possible that the response of the TIC device plus package lasts only for the 20-ns duration of the radiation pulse.

Table II-2 and Figs. II-3 and -4 can be used to estimate displaced charge (Table II-5) for some of the elements at 899 rad(Si) (1-MeV photons).

TABLE II-5

CALCULATED CHARGE DISPLACEMENT FOR TIC AND PACKAGE ELEMENTS

<u>Element</u>	<u>Charge Displaced</u>
0.04-in.-diam, 0.220-in.-high Mo pin	95 pC
0.005-in.-diam Pt bond wire	66 pC/in.
20 000-mil ² , 0.7- μ m-thick W electrode	1.6 pC
20 000-mil ² of 0.030-in.-thick sapphire under W electrode	250 pC

(a)

(b)

Fig. II-6. Dummy glass envelope (no tube) touching the Febetron faceplate. Anode = 60 V; heater = 33 V. (a) Top trace is the grid pin voltage; bottom trace is the cathode pin voltage. (b) Shield pin voltage.

(a)

(b)

Fig. II-7. Triode in a glass envelope touching the Febetron faceplate. (a) Top trace is the grid voltage; bottom trace is the cathode voltage. (b) Shield voltage.

(The average energy of a Compton electron from a 1-MeV photon is 0.6 MeV. The diameters of the molybdenum pin and the sapphire thickness are both greater than the range of an electron at 0.6 MeV. The charge displaced was estimated by using the electron range for the thickness, x .)

The calculated charge agrees reasonably well with the measured charge, particularly since the TIC devices were in the noisy environment of the Febe-tron room (rather than in the screen room). Further, the calculations indicate that the response of the device electrode (1.6 pC) is negligible compared with the responses of the molybdenum pins, bond wires, and sapphire substrate. That is, the photoresponse is dominated by the support structure rather than by the intrinsic TIC device.

3. Verification Tests. The next sequence of tests was performed to verify $\dot{\gamma}$ response mechanisms and to develop TIC structures that would have reduced $\dot{\gamma}$ response. Tests were performed on active TIC devices and on a series of selected electrode structures. In these tests, the package, pins, and bond wires were shielded from the radiation so that only the actual device response was measured. In addition, these tests were performed in the screen room in order to reduce the noise level.

First, the dual triodes were retested in the screen room. The triodes were shielded by a lead brick with a 3/8-in.-diam hole. This arrangement allowed exposure of all devices and some of the interconnect metal but shielded the bond pads, bond wires, and package from the radiation. The areas exposed to the radiation are given below.

Grid	8700 mil ² total (2200 mil ² active)
Cathode	11 300 mil ² total (3000 mil ² active)
Shield	95 000 mil ² total

Total dose for the 20-ns pulse measured 6.38 rad(Si). The results are shown in Fig. II-9.

(a)

(b)

Fig. II-8. Triode in a metal envelope touching the Febetron faceplate. (a) Top trace is the grid voltage; bottom trace is the cathode voltage. (b) Shield voltage.

(a)

(b)

Fig. II-9. Dual triode with package, bond wires and bond pads shielded from radiation. (a) Top trace is the grid voltage; bottom trace is the cathode voltage. (b) Top trace is the shield voltage; bottom trace is the pin diode response.

The displaced charge for the electrodes can be determined from this figure (although not very accurately for the grid and cathode). The measured charge and calculated charge displaced from 30-mil sapphire for 1-MeV photons are given in Table II-6. (Q_G , Q_K , Q_S are the charges displaced from the grid, cathode, and shield respectively.) Again, the 0.6-MeV electron range of 22 mils is used for the sapphire thickness in making the calculation for charge displaced. The calculated charge from the metal electrode is again insignificant, because for the 7000-Å-thick tungsten film, the ratio of charge displaced from the metal to the charge displaced from the sapphire is

$$\frac{q_W}{q_{Al_2O_3}} = \frac{199 \times 0.7 \times 10^{-4}}{39 \times 0.0570} = 6 \times 10^{-3} \quad (II-19)$$

In addition, Table II-6 indicates that displaced charge scales with electrode area.

TABLE II-6

MEASURED AND CALCULATED DISPLACEMENT CHARGE FOR THE DUAL TRIODE
(The measured values for Q_G and Q_K are not very accurate.)

	<u>Measured</u>	<u>Calculated</u>
Q_G	~1.2 pC	0.8 pC
Q_K	~1.2 pC	1.0 pC
Q_S	9.0 pC	8.7 pC
Q_S/Q_G	~7.5	10.9
Q_S/Q_K	~7.5	8.7

Two additional devices were fabricated to test the response of thin metal electrodes on sapphire substrates. Each device consisted of a large and a small electrode as shown in Fig. II-10. Titanium was used for the electrodes on one device and tungsten was used for the other because of their widely differing Z numbers. In both cases, the sapphire was 30 mils thick and the electrodes were 5000 Å thick.

The calculated displacement charges for the tungsten, titanium, and sapphire for a total dose of 6.38 rads are shown below.

$$q_W = 199 \times 0.5 \times 10^{-4} \times 6.38 = 63 \times 10^{-3} \text{ pC/cm}^2$$

$$q_{Ti} = 45.4 \times 0.5 \times 10^{-4} \times 6.38 = 14 \times 10^{-3} \text{ pC/cm}^2$$

$$q_{Al_2O_3} = 39 \times 0.057 \times 6.38 = 14 \text{ pC/cm}^2$$

The response of the tungsten should be 4.5 times greater than that of the titanium, but both responses are negligible compared with that of the sapphire.

The responses of the tungsten and titanium films are shown in Figs. II-11 and -12, and the measured charge and calculated charge for each electrode are given in Table II-7. While the calculated value is low by a factor of 2, the charge scales with area as expected, and the high Z material does not produce more charge. Further, it appears that the response of metal electrode test structures on a sapphire substrate is the same as the response of the electrodes in an operating TIC gain device.

These tests indicate that the dominant mechanisms in the TIC $\dot{\gamma}$ photore-
sponse are the Compton scattering of electrons in the sapphire substrate. These
electrons are replaced by charge flowing from electrode to substrate; this
charge produces the response seen in the $\dot{\gamma}$ tests. The sapphire dominates the
response because its volume is much larger than that of the electrodes.

The obvious way to reduce the $\dot{\gamma}$ response is to reduce the substrate thickness. Further, a ground plane on the back of the sapphire should supply about half of the replacement electrons and so should reduce the $\dot{\gamma}$ response by about a factor of 2. In order to verify this, the test structure shown in Fig. II-13 was designed with a metal back plane that could serve as a ground plane for one of the two electrodes. Three such devices were fabricated: one with 30-mil sapphire, one with 10-mil sapphire, and one with 25-mil alumina.

Fig. II-10. Device schematic for testing response as a function of area. One area is ~ 4 times the other.

Fig. II-11. Test results for different area devices using tungsten films. Top trace is the large area device, and bottom trace is the small area device.

Fig. II-12. Test results for different area devices using titanium films. Top trace is the large area device, and bottom trace is the small area device.

Fig. II-13. Ground plane test structure.
Each electrode is 0.318 cm^2 .

TABLE II-7

MEASURED AND CALCULATED DISPLACEMENT CHARGE FOR
TUNGSTEN AND TITANIUM ELECTRODES
(Large electrode is 28.7 mm^2 ; small electrode is 7 mm^2 .)

$$A_{\text{large}}/A_{\text{small}} = 4.1$$

	<u>Measured</u>	<u>Calculated</u>
Tungsten Electrodes		
Q_{large}	7.8 pC	4.0 pC
Q_{small}	1.8 pC	0.98 pC
$Q_{\text{large}}/Q_{\text{small}}$	4.3	4.1
Titanium Electrodes		
Q_{large}	8.5 pC	4.0 pC
Q_{small}	2.0 pC	0.98 pC
$Q_{\text{large}}/Q_{\text{small}}$	4.3	4.1

A second purpose of this test structure was to determine whether or not the single crystal sapphire became conductive during the radiation pulse. This could be determined by applying a bias voltage to the back plane. The 25-mil alumina test device was fabricated because it was felt that polycrystalline (amorphous) alumina (or radiation-damaged sapphire) was much less likely to become conductive.

The test results are shown in Figs. II-14 through -16. Table II-8 shows the measured and calculated charges with no bias between the electrodes and back plane. As can be seen, the response is reduced by roughly a factor of 2, and the agreement between measured and calculated values is reasonable.

Each test was rerun with +100-V, -100-V, and +500-V biases between the back plane and the electrodes; the results are also shown in Figs. II-14 through -16. The sapphire does indeed become conductive during the radiation pulse. The peak response of the electrode with a back plane is increased by a factor of 7 for the 30-mil sapphire and by a factor of 24 for the 10-mil sapphire when 100-V bias is applied. However, the alumina shows no increase for 100 V and only an increase of 50% with a 500-V bias.

(a)

(b)

(c)

(d)

Fig. II-14. Ground plane test structure results using 30-mil-thick sapphire substrate. In all cases electrode B is the top trace, and electrode A is the bottom trace. The potential difference between the ground plane and the electrodes is (a) 0.0 V, (b) +100 V, (c) -100 V, (d) +500 V.

(a)

(b)

(c)

(d)

Fig. II-15. Ground plane test structure results using 10-mil-thick sapphire substrate. In all cases electrode B is the top trace, and electrode A is the bottom trace. The potential difference between the ground plane and the electrodes is (a) 0.0 V, (b) +100 V, (c) -100 V, (d) +500 V.

(a)

(b)

(c)

(d)

Fig. II-16. Ground plane test structure results using 25-mil-thick alumina substrate. In all cases electrode B is the top trace, and electrode A is the bottom trace. The potential difference between the ground plane and the electrodes is (a) 0.0 V, (b) +100 V, (c) -100 V, (d) +500 V.

TABLE II-8

MEASURED AND CALCULATED RESPONSE OF THE GROUND PLANE TEST STRUCTURES

<u>Structure</u>	<u>Charge (pC)</u>	
	<u>Measured</u>	<u>Calculated</u>
30-mil sapphire		
without ground plane	4.4	5.7
with ground plane	2.4	3.9
ratio	1.8	1.5
10-mil sapphire		
without ground plane	3.2	2.6
with ground plane	1.1	1.3
ratio	2.9	2
25-mil alumina		
without ground plane	3.3	5.7
with ground plane	1.8	3.2
ratio	1.8	1.8

Because the single crystal sapphire becomes conductive during the radiation pulse, the radiation response of a circuit will be increased under normal bias conditions. However, the use of doped sapphire, neutron-irradiated sapphire, or alumina will greatly reduce this effect. The responses shown in Figs. II-14 through -16 were used to estimate the RIC for the 30- and 10-mil sapphire substrates and the 25-mil alumina substrate; these values are shown in Fig. II-17. For reference, the extrapolated values of the room temperature RIC [from (1)] for the undoped and doped sapphire are between the dashed lines in Fig. II-17. (The extrapolation is over much too large a range to be useful. Values of RIC for potential TIC substrate materials need to be measured in the 10^8 rad/s range and up.)

The estimated values of conductivity can be used in Eq. (II-18) to calculate the point at which RIC effects are about the same as Compton effects. The results, plotted in Fig. II-18, indicate that RIC effects may dominate in undoped sapphire for thicknesses in the 5- to 10-mil range. On the other hand, 1-mil alumina may have lower RIC effects than 10-mil sapphire. This emphasizes the importance of evaluating doped sapphire, neutron-irradiated sapphire, and alumina for TIC substrates.

In order to substantially reduce the response of the substrate, a structure such as that shown in Fig. II-19 could be used. This structure lessens

Fig. II-17. Estimated (dashed) and measured substrate conductivity as a function of dose rate.
T = 294K.

Fig. II-18. Voltage as a function of wafer thickness for which RIC effects are approximately the same as Compton scattering effects.

the mass of insulator used for device isolation and, with ground plane and heater, shields the large volume portion of the substrate used for mechanical support. Such a structure might be fabricated by brazing two sapphire wafers together and then grinding and polishing one wafer to a thickness of about 1 mil. A second method might be to deposit a film of insulator on top of a ground plane.

In order to test this structure, 3000 Å of SiO_2 were deposited on a metallized 30-mil sapphire wafer. Then, two 0.25-cm^2 electrodes were fabricated on the SiO_2 . The test results are shown in Fig. II-20. The response appears to be noise with maximum amplitude of 30 μA (3-mV, 100- Ω sense resistor) for $\dot{\gamma} = 4.1 \times 10^8 \text{ rad(Si)/s}$. This test verifies that the structure proposed in Fig. II-19 could substantially reduce the effect of displaced charge from the substrate in a TIC circuit or device. It must be noted, however, that the test structure using glass at room temperature only demonstrates feasibility. A structure using appropriate refractory materials must be developed as part of a follow-on program.

E. Dose Rate Response of the Flip-Flop

The gamma dose rate response of the flip-flop has been calculated and measured to determine how photocurrents induced in TIC devices affect the performance of a complete circuit. Then, the dose rate tolerance of a flip-flop utilizing improved substrates and device structures is calculated. The radiation tolerance of the flip-flop is projected to improve from the current $2 \times 10^9 \text{ rad(Si)/s}$ to $4 \times 10^{11} \text{ rad(Si)/s}$ with improved devices, narrower metal interconnects, and a substrate consisting of a 1-mil insulator on a ground plane on a 30-mil sapphire wafer. The effects of radiation-induced conductivity are not included in the projection since it appears that radiation-induced conductivity can be minimized by doping the sapphire, radiation-damaging the sapphire, or by using the alumina as the substrate.

1. Simplified Analysis of Flip-Flop Sensitivity to Radiation. A schematic of the fully connected flip-flop is shown in Fig. II-21. Neglecting RIC, the most sensitive nodes will be the output-input cross-coupling nodes (A and B) and the nodes at the output of the gain stages (C and D). Since the associated electrodes must replace electrons ejected from the sapphire, the node potentials will increase by an amount

Fig. II-19. Thin insulator on metal ground plane as an improved transient radiation substrate.

Fig. II-20. Response of improved transient radiation substrate.

Fig. II-21. Circuit diagram of the fully interconnected flip-flop.

$$\Delta v_n = \frac{-\Delta Q_n}{C_n}, \quad (II-20)$$

where ΔQ_n is the total replacement charge supplied by node n and C_n is the total capacitance associated with node n . The most sensitive nodes should be the output-input nodes because an increase of 3-4 V (the logic swing of this particular inverter) will turn on both inverters and the state of the flip-flop will be lost.

If RIC is important, then any signal node that is at a voltage substantially different from ground could be affected; in this case, the output nodes of the gain stages (nodes C and D, Fig. II-21) could well be the most sensitive. However, since it has been shown that substrates can be developed with substantially reduced RIC, the effects of RIC will not be included in this analysis.

In order to calculate the upset level of the flip-flop, it will be assumed that the critical nodes are the output-input nodes. Then from Eq. (II-20), the photon-induced charge and capacitance of these nodes must be calculated. The calculations will include the grid of the gain device T1 (or T6), the grid-cathode-cathode shield (G-K-KS) structure of the level shift diode T9 (or T4), the anode of the level shift diode T10 (or T5), plus the interconnect metal. Because the circuit is symmetrical and because the area of the interconnect metal is the same for both nodes, the $\dot{\gamma}$ response will be the same for either node.

In calculating the replacement charge for an electrode, it is assumed that the electrode must replace the charge in the sapphire below it and half the charge in the sapphire between it and the next electrode or ground plane. The effective area for radiation effects, A_R , includes the area of the electrode and half of the area between it and next electrode. The equations in Section II.D are used to calculate the replacement charge per rad (S_1) when radiation occurs in a time that is short compared with the circuit response time.

In Table II-9 the actual area A , the effective area A_R , the displaced charge per rad Q/γ , and the calculated capacitance to ground C are shown for each electrode as well as the totals. In addition, the rads required to increase the voltage at each electrode and output-input node by 2 V are calculated (an increase of about 2 V would drive both inverters on and upset the flip-flop). In this calculation the entire radiation pulse is assumed to be

delivered in a time that is short compared with the response time for the circuit. The last row shows the corresponding dose rate for a pulse width of 20 ns. The calculations indicate that the flip-flop could withstand 45 rad(Si) in a short period or a dose rate of 2×10^9 rad(Si)/s in 20 ns.

TABLE II-9

GAMMA/GAMMA-RATE-INDUCED RESPONSE IN TIC FLIP-FLOP TEST STRUCTURE

	<u>Grid</u>	<u>G-K-KS</u>	<u>Anode</u>	<u>Interconnect</u>	<u>Total</u>
A(mil ²)	485	4567	3960	3400	12412
A _R (mil ²)	903	6232	4480	6800	18415
Q/γ[C/rad(Si)]	17.4×10^{-15}	120×10^{-15}	85.9×10^{-15}	130×10^{-15}	353×10^{-15}
C(pF)	2.01	0.60	0.52	2.90	8.0 ^a
γ[rad(Si)] ^b	231	10.0	12.1	44.6	45.3
γ[rad(Si)/s] ^c	1.2×10^{10}	5×10^8	6×10^8	2.2×10^9	2.3×10^9

^aIncludes 2 pF from the package pin to ground (measured).

^bTo induce a change of 2 V.

^cPulse width = 20 ns.

The first four rows in Table II-9 show the additive contributions of each electrode, while the last two rows indicate how the response of an electrode by itself compares with the overall response. For example, the γ tolerance of the G-K-KS structure is low compared with the total response, and its Q/γ contribution is high. Therefore, reducing the area of the G-K-KS structure would produce the largest improvement in the flip-flop γ tolerance. On the other hand, the γ response of the interconnect metal is about the same as the total response. Thus, reducing the area of the interconnect metal would produce little effect on the overall γ tolerance, but would improve the flip-flop's frequency response because the node capacitance would be reduced.

2. Flip-Flop Proton Dose Rate Tests. A TIC flip-flop was tested in a 647-MeV proton beam at the Los Alamos WNR facility. During the tests, the flip-flop was triggered continuously at a 4-kHz rate. The outputs were fed to line drivers so that they could be monitored in the control room.

As discussed in the previous section, the upset level of the flip-flop is expected to be determined by the total dose received in a period of time that is short compared with the flip-flop response time. In the case of $\dot{\gamma}$ upset, electrons are ejected from the substrate, and upset is caused by electron replacement current. The $\dot{\gamma}$ upset level is calculated to occur for a dose of 45 rad(Si) in a short period of time. However, the proton upset mechanism should be somewhat different in that the protons impart less energy to the electrons and the electron motion is much less directional. Therefore, the number of ejected electrons will be lower, but the number of electron-hole pairs generated, and the associated conductivity effects, will be greater for protons.

The pulse width of the proton beam was adjusted until the flip-flop was at the threshold of upset, which occurred for a pulse width of 200 ns and a dose rate of 1.4×10^8 rad(Si)/s, or a total dose of 28 rad(Si). Figure II-22 shows the normal waveform, and Figs. II-23 and -24 show the effect of the proton beam on the flip-flop. (In Figs. II-23 to -26, the scope was triggered 20 μ s before the proton pulse.) In Fig. II-23, the flip-flop was not upset, although a comparison with Fig. II-22 indicates that it was on the verge of being upset. In Fig. II-24, the flip-flop was upset, as it changed state when hit with the proton beam. Thus, the flip-flop's upset threshold is 28 rad(Si) delivered in 200 ns, which is a short time compared with the flip-flop's response time.

The initial voltage step in Figs. II-23b and II-24c is caused by replacement current for the ejected electrons during the 200-ns pulse. If ejected electrons were the only radiation-induced mechanism, the off output would require about a 2-V step to upset the flip-flop. Since the induced step in Figs. II-23b and II-24c is no more than 1/2 V, other mechanisms such as conductivity effects must be present.

The flip-flop response was also measured for a proton beam pulse width of 900 ns for a dose of 192 rad(Si). From the results shown in Figs. II-25 and II-26, it can be seen that the higher dose drives both outputs negative. It can also be seen that the responses of the two sides are not symmetrical. This likely reduces the dose rate tolerance of the flip-flop.

To summarize, the measured proton upset level of this flip-flop is 28 rad(Si) in a short period of time (1.4×10^8 rad(Si)/s for 200 ns), as compared with the calculated gamma level of 45 rad(Si). That is, for a 20-ns pulse, the

Fig. II-22. Undisturbed flip-flop waveform.

(a)

(b)

(c)

Fig. II-23. TIC flip-flop response for 200-ns proton beam pulse width, 28 rad(Si), out 1 initially low, out 2 initially high. (a) Out 1 top trace, out 2 bottom trace, 50 μ s/div; (b) out 1, 50 μ s/div; (c) out 2, 5 μ s/div.

(a)

(b)

(c)

Fig. II-24. TIC flip-flop response for 200-ns proton beam pulse width, 28 rad(Si), out 1 initially high, out 2 initially low. (a) Out 1 top trace, out 2 bottom trace, 50 μ s/div; (b) out 1, 5 μ s/div; (c) out 2, 5 μ s/div.

(a)

(b)

(c)

Fig. II-25. TIC flip-flop response for 900-ns proton beam pulse width, 192 rad(Si), out 1 initially low, out 2 initially high. (a) Out 1 top trace, out 2 bottom trace, 50 μ s/div; (b) out 1, 5 μ s/div; (c) out 2, 5 μ s/div.

(a)

(b)

(c)

Fig. II-26. TIC flip-flop response for 900-ns proton beam pulse width, 192 rad(Si), out 1 initially high, out 2 initially low. (a) Out 1 top trace, out 2 bottom trace, 50 μ s/div; (b) out 1, 5 μ s/div; (c) out 2, 5 μ s/div.

proton dose rate for upset is 1.4×10^9 rad(Si)/s, and the calculated gamma dose rate for upset is 2×10^9 rad(Si)/s. The device, circuit, and process improvements designed to improve the TIC $\dot{\gamma}$ tolerance should produce similar improvements in the proton dose rate tolerance. In particular, the reduction of substrate RIC should substantially improve the proton dose rate tolerance.

3. Projected Improvements. The radiation tolerance of a TIC circuit can be improved in four ways: (1) by reducing the size of the devices and metal interconnects, (2) by reducing the effective thickness of the substrate, (3) by increasing the logic voltage swing, and (4) by changing substrate materials. In this section, the radiation tolerance of the flip-flop will be recalculated both for reduced circuit size and for reduced wafer thickness in order to project transient radiation tolerances expected from circuits incorporating the knowledge gained to date.

The circuit area can easily be reduced by using smaller devices and narrower and shorter metal interconnects. The device used will be the redesigned device discussed in Section III.D. This device has a cathode width of 0.8 mils and cathode length of 19.9 mils. The grid-cathode structure and the anode of this device each have an area of 63 mil^2 rather than the nearly 4000 mil^2 of the test device.

The width of the interconnect metal can also be reduced. The 4-mil metal width and 4-mil spacing were used in devices tested to date in order to simplify the mask generation, not because of process limitations. Figures II-27 and -28 show the dose rate required to produce a 2-V change of potential on the metal as a function of the metal width for 10- and 1-mil substrates (it is assumed that the metal width and metal-to-ground shield spacing are the same). Also shown is the capacitance per unit length. Decreasing the metal width improves the radiation tolerance of the metal substantially. However, as was pointed out previously, decreasing the area of the metal yields diminishing returns when other parts of the circuit are dominant, although reducing the metal width still improves the frequency response by reducing circuit capacitance. Therefore, a metal width of 1 mil will be chosen for the following calculations. This dimension is compatible with device size and required device spacing and provides only a small contribution in radiation-induced current. The layout used for the following calculations is the improved flip-flop layout discussed in Section III.D and shown in Fig. III-30.

Fig. II-27. Dose rate for upset vs metal width on a 10-mil sapphire substrate. (2-V threshold)

Fig. II-28. Dose rate for upset vs metal width on a 1-mil sapphire substrate. (2-V threshold)

The greatest improvement in radiation tolerance will be obtained by reducing the thickness of the substrate. Circuits can be fabricated on substrates in the 6- to 10-mil range, but substantially thinner substrates will require other fabrication methods. As described previously and demonstrated by the last γ test described in Section II.D.3, a layered structure consisting of a thin insulator on a metal ground plane on a support layer has been found to be effective in decreasing the radiation-induced current of the substrate. The radiation tolerance of the improved flip-flop was calculated for substrate thicknesses ranging from 30 mils down to 1 mil. Figure II-29 shows the calculated upset level for a 20-ns radiation pulse and the capacitance at the output-input node as a function of substrate thickness.

The upset level was calculated for both 2-V ($\Delta V = 2$) and 20-V ($\Delta V = 20$) induced excursions on the output-input node. The previous calculations were for 2 V because the logic swing of the current test flip-flop is 3-4 V. However, a logic swing of 30-50 V is feasible with vacuum triodes; at this level an excursion of 20 V or more would be required to upset the flip-flop.

As can be seen from Fig. II-29, the node capacitance increases for thinner substrates. This improves the radiation tolerance but degrades the frequency response slightly. If capacitance remained constant, the upset level vs thickness would be a straight line for a fixed layout.

The improved layout on 30-mil sapphire only improved the radiation tolerance from 2×10^9 rad(Si)/s to 6×10^9 rad(Si)/s for $\Delta V = 2$. However, a 10-mil substrate improved this to 2×10^{10} , and a 1-mil substrate brought the calculated tolerance up to 4×10^{11} rad(Si)/s for $\Delta V = 2$. (The effect of the heater as a ground plane was not included in the calculations. Including this would double the calculated tolerance.) If the flip-flop is designed with a logic swing of 30 V, the calculated upset level for a 1-mil substrate is 4×10^{12} rad(Si)/s.

F. Conclusions

1. The physics of the response of the TIC structure has been modeled and measured. Analyses and observations were found to be in good agreement.
2. Photon (γ)-induced effects in the substrate were found to be dominant in current TIC structures. Depending on substrate material,

Fig. II-29. Upset level and node capacitance as a function of substrate thickness for the improved flip-flop layout.

the dominant effect is either photoconductivity or displacement current.

3. A substrate with a ground plane and thin insulator over the ground plane was proposed to reduce the effects of the substrate described above. Preliminary tests were run that verified the effectiveness of this structure.
4. Flip-flops using the same circuit tested but incorporating the improved substrate and 1-mil lithography were analyzed yielding predicted upsets of between 4×10^{11} rad(Si)/s and 4×10^{12} rad(Si)/s depending on the logic level employed ($\Delta V = 2$ V or $\Delta V = 20$ V).

G. Recommendations

1. Techniques for manufacturing the improved substrate described above must be investigated.
2. Continued $\dot{\gamma}$ tests must be performed and compared with theory.
3. Extended total dose tests must be conducted to determine failure levels.
4. EMP tests/failure analyses must be conducted.

III. LEVEL OF INTEGRATION

A. Statement of Work from Proposal (March 1982)

"The electronic sophistication and complexity of modern weapons has in recent years derived from the evolution of integrated circuitry (Fig. III-1). Clearly, by comparison, the TIC technology is in a very early stage of development both in terms of technology and investment.

"Although the ultimate performance limitations and radiation hardness of the TIC technology will be dependent on the technology specific to TIC production and performance, the analogy of this technology to early integrated circuits is strong enough to base the key features of a program on the lessons learned in the development of IC technology; namely that progress has been due to improvements in four areas.

- o Device processing allowing smaller devices and higher yields
- o Device technology, allowing higher performance per device
- o Larger chips, allowing more complicated functions and higher reliability

- o Clever circuit design techniques that take advantage of the particular benefits of the process and overall technology, allowing more circuit sophistication, more combined functions, and less isolation between devices

The DOE investment in this technology to date (as of March 82 proposal) has been on the order of \$600k. Technology to date puts us in the 10 to 100 devices per chip regime; and current technology refined but applied in 'brute force' form to circuitry puts us in the 1000 (for analog) to 5000 (for digital) device per chip regime. (Figure III-2 compares current TIC technology to the classic silicon IC learning curve.)

"The objective of this portion of this one-year program will be to enhance assessments of possible short- and long-term levels of integration from which potential applications can be evaluated.

"Factors limiting the level of integration can be divided into process-related and process-independent categories. Process-related limitations are expected to be due to extraneous currents from two sources. The first is resistive leakage from element to element and the second is spurious emission from elements such as grids, anodes, and shields, which are not intended to emit. Another fundamental process limitation is cathode photolithography. The extraneous currents determine how large a device must be for device bias currents to mask secondary currents. The cathode photolithography determines how wide the cathode stripe must be for proper delineation.

"Process-independent limitations are electrostatic interactions between devices and electron confinement within a given device (Figs. III-3 and -4 respectively). Both of these effects combine to determine how far apart devices must be to ensure electrical isolation.

"A typical present device is made with seven 1.5-mil-wide cathode stripes per device, with 1.0-mil-wide grid stripes interdigitated between cathodes. Shield electrodes are used around the grid-cathode structure to produce equipotential lines that confine electron paths within a specific device.

"Electrostatic interactions can be understood by inspecting Figs. III-3 and -5. It is desired that the grid cathode structure GK1 of a particular device not have the electric field at its surface appreciably modified by potentials applied to a neighboring grid cathode structure GK2, or to a neighboring anode shield SA. This is achieved by adjusting the device-to-device spacing

Fig. III-1. Evolution of silicon integrated circuits. Progress has been due to processing, devices, larger chips, and clever circuit design techniques.

Fig. III-2. Projections made using current TIC technology. The TIC chip size is 0.19 in^2 .

Fig. III-3. Electrostatic device interactions.

ELECTRON CONFINEMENT

- WANT TO AVOID

- USE SHIELD TO FORM ELECTROSTATIC "BOTTLES"

Fig. III-4. Typical interactions.

Fig. III-5. Electron confinement. Dimensions are in mils.

to a distance at which the fields from other elements are compatible with circuit requirements (e.g., low gain digital allows very close spacing, whereas high gain linear requires increased isolation). An advanced TIC circuit design technique will undoubtedly utilize these interactions advantageously.

"The electron confinement aspect is illustrated in Fig. III-4. Electrons emitted from the cathode of a given device must be collected by the anode of that device and not attracted to neighboring anodes that might be at different potentials. In this case, shield electrodes can ensure this. If the shield potential is properly chosen, a zero-potential line relative to the cathode potential is produced that confines the electrons to the device by an electrostatic bottle. Present devices incorporate appropriate shield electrodes to produce electron confinement.

"The simple device arrays tested to date have been at a level of integration of 122 devices/in². As was seen in Fig. III-5, analytical predictions indicate that a level of 1000 devices/in² can be achieved with less than 1% interaction between neighboring devices, which would represent an acceptable level for 'straight forward' analog circuit design (digital might easily allow for 5000 to 10,000 devices/in².) At this level of integration, electron confinement is also easily achieved. The reduction of leakage current to an acceptable value at this level of integration has not yet been tested. Spurious emission and methods for its suppression have been addressed in previous programs. It is not expected to be a limitation at this level.

"Current photolithography allows cathode-to-grid spacings on the order of 0.2 mils and is, therefore, not a limitation at even 100,000 devices/in². The ratio of grid-cathode areas to total device/shield area for a projected minimum size device with present brute force circuit technology is 1/33. Most of the device area is used by shield electrodes. Therefore, clever circuit design and/or advances in device morphology, which reduce the need for large shields, must be developed to fully exploit the level of integration possible utilizing existing cathode and metal photolithography.

"Measurements must be made to quantify amounts and locations of sources of leakage currents and spurious emission as a function of activation techniques and as a function of time. Techniques will be investigated to improve results.

"No activities are proposed in cathode delineation because present techniques are adequate.

"A mask set will be generated and devices fabricated to measure interactions and electron confinement. The masks will include devices with one, three, and six cathode stripes. A four-device nearest neighbor array will be used (Fig. III-6). Electron confinement will be measured as a function of electrode bias voltages. Interactions will be measured and their effects evaluated for simple two- and four-device circuits such as simple gain stages, cathode followers, and differential amplifiers. Effects of reducing device geometry on device parameters such as μ , g_m , etc., will also be evaluated."*

B. Modification to the Statement of Work

Because the generation of artwork and mask making for new test structures is time consuming and costly relative to the budget for this program and because an integrated flip-flop or memory element fabricated using TICs was required to check transient radiation upset predictions, the Statement of Work was modified as indicated below.

1. Fabricate and test simple circuit, i.e., gain stages with masks on hand and compare the test results with interaction predictions based on two-dimensional Laplace-equation computer codes. Analytic circuit models incorporating electrostatic feedback terms were to be developed and used to compare the predicted with the observed circuit performance.
2. Build a first completely integrated circuit using TICs, which would force verification of expected performance levels.
3. Quantify sources of parasitic resistive grid-to-cathode leakage and emission from noncathode elements.
4. Improve fabrication processes to minimize leakage and spurious emission. This aspect was considered critical to achieving a high level of integration.
5. Evaluate, using masks on hand, the four nearest neighbor interactions as described in the March 1982 Statement of Work.

C. Process Dependent Factors Influencing Level of Integration

1. Resistive Leakage. TIC devices incorporate photolithographically delineated thin films on sapphire substrates. The spacing between thin-film

*End March 1982 Statement of Work.

elements such as grids and cathodes can currently be as narrow as 5 μm (0.2 mil). Resistive leakage between such elements can be detrimental to efficient circuit operation; therefore, quantifying the amount and sources of leakage and improving fabrication techniques to minimize leakage have recently been major activities of this program. The test vehicle used is the dual triode shown in Fig. III-7. Each triode has ten 100-mil x 1.5-mil cathode lines for a total cathode area of 1500 mils². The grid-to-cathode spacing is 0.3 mils, and the total grid-cathode close proximity length is 2000 mils. This test structure was designed to provide an extensive grid-to-cathode length, which allows for easily measurable resistances for very small amounts of leakage-causing residue.

From the outset, the cathode-coating/photoresist combination was strongly suspect as a possible source of leakage. This combination is a mixture of standard vacuum tube barium-strontium-calcium carbonate powder and negative photoresist. Verification of this mixture and the associated processing as the leakage source was made by assembling dual triode substrates without cathode material or photoresist and then processing them through the normal vacuum bakeout and activation cycle, heating both substrates to more than 900°C. No measurable leakage was observed. However, at this point in time, grid-to-cathode leakages as low as 100 k Ω were commonplace in the test structures with cathode/photoresist material. This same type of test, when conducted with only the negative photoresist binder portion of the cathode-coating mix, indicated that the negative photoresist binder (no added carbonates) was the principal source of the observed leakage. The negative resists used are basically cyclized rubber derivative with a sensitizer additive. (Positive resists cannot be used because they contain sulphur compounds that react with barium to "poison" cathode emission.) Observations during the activation cycle show that, at approximately 700°C, leakage started to form, and at that time, various hydrocarbon outputs were observed on a mass spectrometer. For completeness, several brands of negative resist were evaluated with little or no difference observed.

A series of tests was then performed to determine the extent to which the vacuum pumping path and temperature variation across the substrate governed the magnitude and location of hydrocarbon deposits. In the first tests, only the grid-cathode substrate (Fig. III-7a) was used, and cathode coating

Fig. III-6. Nearest neighbor arrays.

(a)

(b)

Fig. III-7. Dual triode for leakage evaluation.

was applied to only one triode. A small-diameter nickel wire was positioned over this device to serve as an anode with approximately 100-mil vertical spacing. Therefore, this device had essentially an unrestricted pumping path to the vacuum pump. Grid-cathode leakage on both triodes was monitored during the activation cycle. Typical results are shown in Fig. III-8.

These data show that with unrestricted pumping, the leakage on the cathode-coated device stabilized at $\sim 3 \text{ M}\Omega$ after 3 h at temperature and also indicate that some of the hydrocarbon residue had reached the uncoated device.

This test was then repeated using the regular anode substrate in place of the nickel wire with a 40-mil separation between substrates. This provides the restricted pumping typical of TICs. Results are shown in Fig. III-9.

It is obvious from this test that restricted pumping during activation enhances the deposition of leakage-causing materials. This test was performed with both substrates heated simultaneously. The anode-to-anode shield leakage was in the megohm range. Additional tests were performed with the anode substrate heater turned off. Hydrocarbons were observed to condense on the relatively cool surface, promoting an order of magnitude increase in anode-anode shield leakage. The heater pattern used on the aforementioned substrates is shown in Fig. III-10.

The current assembly technique for the two substrates uses three 40- x 50-mil platinum straps bonded to each substrate at 120° intervals. The substrates are then aligned with respect to each other. By viewing the "cross" and "tee" alignment keys shown on the circuit patterns (Fig. III-7), the heater windows permit viewing these keys. Nickel shims welded to the straps govern the substrate separation. With the substrates aligned and spaced by the shims, the corresponding straps are welded together external to the substrates. Unfortunately, these straps also create a heat sink for three areas of the substrates. Temperature measurements indicated a $40\text{--}50^\circ\text{C}$ differential from the substrate center to the area of a strap with a corresponding potential for increased leakage between elements in this area.

2. Resistive Leakage - Improvements to Date. Based on the measurements and mechanisms observed in the tests described above, three obvious approaches to reduce the leakage were investigated.

- o Minimize the amount of photoresist used in the cathode mixture.
- o Reduce the effects of the poor pumping path.
- o Redesign the heater to provide more uniform substrate temperature.

Fig. III-8. Leakage vs time for a triode with an unrestricted pumping path.

Fig. III-9. Leakage vs time for a triode with a restricted pumping path.

Two limitations imposed on a reduction of photoresist used in the mixture are (1) a minimum quantity is required to define photolithographic lines and (2) a minimum quantity is necessary to serve as a binder for the cathode powder. An evaluation of the powder-resist mixture used in the aforementioned tests indicates that additional thinning of the resist would not be practical. However, other modifications of the coating process that result in a net decrease in photoresist are believed worthwhile; they are listed below.

1. A decrease in the coating thickness as applied to the substrate. Because the powder-resist mixture is applied by spinning, an increase in spin speed accomplishes this. The cathode thickness was reduced by approximately 30%.
2. A decrease in the polymerization of the photoresist. Unpolymerized resist should be removed by developer. Also, polymerization increases the length of hydrocarbon chains and the difficulty in vacuum pumping; therefore, the ultraviolet exposure time of the resist was reduced to the minimum for acceptable line delineation. Also, emulsion photomasks were substituted for metal-on-glass photomasks. The emulsion surface reduces light scattering during exposure.
3. An improvement in the developing and postdevelopment process to minimize surface contaminants and insure removal of all unpolymerized resist. A three-bath development sequence was initiated--two developer baths followed by a butyl-acetate rinse, all incorporating ultrasonic agitation. This process was then followed by a 30-min, 120°C-air postbake and a 10-min sputter-etch in argon.

The effects of the poor pumping path were alleviated by incorporating a much longer pumping time before activation (72 h). This is followed by a pre-activation bakeout at 400°C for 15 h. The substrates are then heated to 850°C to complete the activation process. Experiments were performed to vary the bakeout time and temperature and also the rate of heating to 850°C. The times, temperatures, and rates appear to be optimum.

The heater was redesigned using a computer analysis to provide a more uniform wafer temperature, compensating for strap losses, etc. The revised pattern is shown in Fig. III-11.

A number of dual triodes were made using the aforementioned process modifications. The grid-cathode leakage distribution (after stabilizing at 850°C) obtained in these tests is shown in Fig. III-12. These data averaged

Fig. III-10. Original substrate heater design.

Fig. III-11. Revised substrate heater design.

960 k Ω . While this is a considerable improvement over the previous 100-k Ω level, the distribution shown in Fig. III-12 indicates further effort is required for ultimate levels of integration. However, this leakage level has been improved sufficiently to permit the effective operation of circuits with device densities in the 1000 to 10,000 devices/in² regime.

3. Resistive Leakage - Future Improvements. A significant improvement could be made if it were possible to heat individual substrates (with coated cathodes) to 850°C in a vacuum before they were assembled as pairs of substrates and mounted in the device package. This vacuum firing could be performed in a vacuum oven, essentially corresponding to the "unrestricted pumping path" test of Fig. III-8. Unfortunately, the conventional cathode material, barium carbonate, is reduced to BaO during this temperature cycle. BaO, if exposed to air, reacts with the moisture in the air to form barium hydroxide that, as a low melting compound, induces excessive sintering and fusion of the cathode coating, with loss of emission. Therefore, activation, assembly, and packaging would have to be accomplished under vacuum (a technique employed effectively by Plessey a number of years ago for similar reasons in fabrication of vacuum tubes for transoceanic cables). In principle, this technique should be applicable though not appropriate for a laboratory-scale R&D effort.

A more promising approach, therefore, might be the use of barium aluminate as a cathode material. The key factor pertaining here is its ability to withstand repeated exposure to air after activation without deterioration. Coppola and Hughes³ have shown the behavior of a pressed cathode containing barium aluminate under conditions of repeated air exposure (Fig. III-13). As shown, the cathode was able to obtain the initial emission level through five cycles. The TIC would require only one cycle to complete processing. TIC cathodes would be activated in a vacuum system with an unrestricted pumping path, then assembled. Preliminary work performed at Los Alamos using barium aluminate has also shown promise, although much more work must be done to create a cathode material with proper characteristics for application to the TICs.

4. Spurious Emission. Spurious emission is defined as emission from elements other than the cathode. Because all elements, including the wires bonded to the substrates, are at or near cathode temperature in the TIC assembly, the possibility for emission exists if barium or barium oxide is present on the element. Barium or barium oxide may be evaporated from the cathode material during activation or over life. It may also be left on the substrates

Fig. III-12. Grid-to-cathode leakage distribution.

Fig. III-13. Behavior of a pressed cathode containing barium aluminate under conditions of repeated air exposure.

as a result of incomplete development and rinse. In general, all of the improvements incorporated in the process to reduce leakage also act to reduce spurious emission. The use of titanium as the upper layer of grids, anodes, shields, etc., also helps. Hot titanium reacts with barium to form barium titanate; it also reduces BaO and absorbs the oxygen. The platinum bond pads and bond wires remain a problem. However, by reducing their area and shielding by a ground plane, their effects can be minimized. It is also possible to use titanium bond wires or NiTi-brazed lead frames. As with leakage, the spurious emission effects have been sufficiently controlled to permit circuit operation at levels of integration exceeding several thousand devices per square inch.

5. Conclusions on Process Dependent Factors Influencing Level of Integration. Recently a major effort has been made to reduce the parasitic resistive leakage between elements. Experiments confirm that the major source of leakage is residue from the hydrocarbons present in the photoresist that is used as a photosensitive binder to define the cathode pattern. Leakage has been experimentally observed to be increased by the poor pumping path caused by the closely spaced sapphire substrates, by nonuniform heating of the substrates, and by excessive polymerization of the photoresist.

A number of experiments were performed that have resulted in several process modifications to reduce the leakage. The modified sequence with the largest effect is to (1) minimize the amount of photoresist used in the cathode mixture, (2) do a 10-minute sputter etch to remove surface contamination after the normal photoresist developing techniques are completed, (3) use a much longer pumping time (72 h) to remove as many volatiles such as photoresist solvents before activating at high temperature and thereby reduce the effects of the poor pumping path, and (4) bake at 400°C for 15 h before activation to drive off as many remaining volatiles as possible.

In addition, the heater was redesigned to provide a more uniform substrate temperature. This approach minimizes the condensation of hydrocarbons on the cooler areas and reduces edge element leakage.

Spurious emission from electrodes such as grids, anodes, shields, and ground planes is caused by cathode material being deposited on the electrodes during the cathode activation process. Emission is minimized by using titanium as the top layer for these electrodes because cathode material on titanium produces a short-lived cathode. On the other hand, platinum with deposited

cathode material produces a much better parasitic cathode. Spurious emission was further reduced by minimizing the platinum area used for bond pads. Cathodes are activated and the devices are aged for several hours until the spurious emission is reduced to a negligible level by the chemical reaction of the titanium with the cathode materials.

The interelectrode leakage resistances were measured on a number of test devices with typical values ranging from several megohms upward. Most of the leakage paths were geometrically dominated by leakage from the interconnect metalization from device to bond pad, not the device itself. Therefore, the internally connected devices of actual integrated circuits are expected to have substantially higher leakage resistances.

While these problems appear to be solved for simple TICs, leakage and spurious emission must be continuously monitored as TICs become more complex. The additional cathode area required by more complicated circuits, smaller lines and spacings, and process changes made to enhance other parameters all could contribute to increased sensitivity to leakage and emission.

D. Process Independent Factors Influencing Level of Integration

1. Device and Circuit Modeling/Verification of Effects. Because of the nature of TICs and the complex interaction between devices, a substantial device modeling and circuit analysis capability is required to accurately predict performance of a moderately complex TIC. A TIC device has characteristics that are very similar to a conventional vacuum triode. The major difference is that the TIC device, when used in an integrated circuit, can be affected by parasitic electrostatic interactions that can modify the expected device current. Previous analyses and experiments have suggested that the TIC device characteristics can be described by

$$i_P = K(v_G + v_P/\mu + \sum v_S/\mu_S)^{3/2}, \quad (\text{III-1})$$

where i_P = anode current,

K = perveance,

v_G = grid-to-cathode voltage,

v_P = anode-to-cathode voltage,

v_S = voltage on another electrode s in the circuit,

μ = the triode amplification factor, and

μ_S describes the effect of electrode S on the tube characteristics.
The variational anode current is

$$di_P = \frac{\partial i_P}{\partial v_G} dv_G + \frac{\partial i_P}{\partial v_P} dv_P + \frac{\partial i_P}{\partial v_S} dv_S = g_m dv_G + \frac{1}{r_P} dv_P + g_{ms} dv_S, \quad (\text{III-2})$$

where, for simplicity, it is assumed that only the grid, anode, and one additional shield electrode influence the anode current. Then

$$g_m = \partial i_P / \partial v_G = 1.5 K (v_G + v_P/\mu + v_S/\mu_S)^{1/2} = 1.5 K^{2/3} i_P^{1/3}, \quad (\text{III-3})$$

$$\frac{1}{r_P} = \partial i_P / \partial v_P = g_m / \mu, \text{ and} \quad (\text{III-4})$$

$$g_{ms} = \partial i_P / \partial v_S = g_m / \mu_S, \text{ or} \quad (\text{III-5})$$

$$g_m r_P = \mu \text{ and} \quad (\text{III-6})$$

$$g_{ms} r_P = \mu / \mu_S. \quad (\text{III-7})$$

These equations give rise to the linear equivalent circuits shown in Fig. III-14.

Equation (III-1) can also be used to calculate the gain and dc bias of the $\mu/2$ gain stage shown in Fig. III-15. Note that the calculations include the effects of the ground shield and the effects of the anode and cathode shields of both devices. From Eq. (III-1),

$$i_{P1} = K_1 (v_{G1} + v_{P1}/\mu_1 + v_{P1}/\mu_{S1} + v_{PP}/\mu_{P1})^{3/2} \text{ and} \quad (\text{III-8})$$

$$i_{P2} = K_2 [(v_{PP} - v_{P1})/\mu_2 - v_{P1}/\mu_G - v_{P1}/\mu_{S2}]^{3/2}, \quad (\text{III-9})$$

where μ_1 and μ_2 are the amplification factors of the bottom and top triodes, respectively. If $i_{P1} = i_{P2}$, then Eqs. (III-8 and -9) can be solved for the anode voltage v_{P1}

Fig. III-14. Linear equivalent circuits for a TIC gain device. (a) Controlled current source. (b) Controlled voltage source.

Fig. III-15. TIC gain stages. (a) $\mu/2$ with active load. (b) $\mu/2$ including ground, anode, and cathode shields.

$$V_{P1} = \frac{-V_{G1} + V_{PP}(\gamma/\mu_2 - 1/\mu_{P1})}{1/\mu_1 + 1/\mu_2 + \gamma[1/\mu_2 + 1/\mu_{S1} + 1/\mu_G]} , \quad (\text{III-10})$$

where $\gamma = (K_1/K_2)^{2/3}$. The small signal voltage gain is

$$G_v = -1/D , \quad (\text{III-11})$$

and the dc bias voltage is

$$V_{P1} = V_{PP}(\gamma/\mu_2 - 1/\mu_{P1})/D , \quad (\text{III-12})$$

where

$$D = 1/\mu_1 + 1/\mu_{S1} + \gamma(1/\mu_2 + 1/\mu_{S2} + 1/\mu_G) . \quad (\text{III-13})$$

If Tube 1 and Tube 2 in Fig. III-15 are identical, then $\gamma = 1$ and $\mu = \mu_1 = \mu_2$. Then, if μ_{S1} , μ_{S2} , and μ_G are large, $G_v = -\mu/2$ and $V_{P1} = V_{PP}/2$.

As an example, two 60-mil-long test devices were placed end-to-end on the same substrate pair. The measured μ 's are

$$\mu_1 = \mu_2 = 23,$$

$$\mu_G = 64,$$

$$\mu_{S1} = 348,$$

$$\mu_{S2} = 344 \text{ and}$$

$\mu_{P1} = 1254$. For $V_{PP} = 200$ V, the measured and calculated gain and dc levels are

	Calc	Meas
G_v	-9.2	-9.5
V_{P1}	78.7 V	83.4 V .

Note that the interactions have a substantial effect, for without them the gain G_v and the bias point V_{P1} would be -11.5 and 100 V.

2. Device Interactions As stated in the March 1982 Statement of Work, two types of device-to-device interactions are important in the TICs: electron interactions and electrostatic interactions. Electron interactions occur when electrons are not confined to the appropriate device (or devices). For

proper operation of an integrated circuit using TICs, electrons emitted from the cathode of a given device must be collected by the anode of that device and not attracted to neighboring electrodes that might be at different potentials. Electrons can be confined to the appropriate device by means of shield electrodes. If the shield potential is properly chosen, a zero potential line (with respect to the cathode) is formed that confines the electrons to that device. In effect, this zero potential line forms an electrostatic bottle.

Electrostatic interactions are illustrated in Figs. III-3 and -5. It is desired that the grid-cathode structure GK of a particular device not have the electric fields at its surface appreciably modified by potentials applied to a neighboring grid cathode structure GK2 or by a neighboring anode or anode shield. This can be achieved by adjusting device-to-device spacing to a distance at which the fields from other elements are compatible with circuit requirements. That is, low gain digital circuitry would allow relatively close spacing, whereas high gain linear circuitry would require increased isolation.

In evaluating the relative importance of these two effects, it should be noted that electron containment can be achieved with the appropriate potential on a shield whose width is comparable to the device electrode widths, whereas electrostatic interactions decrease continuously with increasing shield width. Therefore, a thorough understanding of electrostatic interactions vs geometry will be required to accurately project future levels of integration. For this reason, a number of devices were fabricated and the electrode interactions were measured. These measurements were then compared with computer calculations; agreement was found to be good. As a result, the computer calculations can now be used to determine the required shielding for the needed degree of isolation. However, a limitation should be noted; that is, the computer code solves the two-dimensional form of Laplace's equation so that only the interactions between adjacent devices such as devices a and d or b and c in Fig. III-16, with electrode lengths much greater than electrode widths, can be calculated. A three-dimensional code will be required to calculate interactions between diagonal or end-to-end devices such as illustrated in Fig. III-16 or between devices with other aspect ratios.

The four-device nearest-neighbor array shown in Fig. III-16 was used to measure the device interactions. Electrostatic interactions were characterized as they were in the previous section in terms of the electrode μ 's, where the μ of electrode i with respect to the cathode of device j, μ_{ij} , is defined as

Fig. III-16. Four-device, nearest-neighbor array to evaluate device interactions.

$$\mu_{ij} \equiv - \frac{\partial v_i}{\partial v_{Gj}} \quad . \quad (\text{III-14})$$

The small signal open circuit voltage gain of a conventional triode is

$$\mu \equiv - \frac{\partial v_p}{\partial v_G} \quad ; \quad (\text{III-15})$$

or in the notation of Eq. (III-14), the gain of triode j is

$$\mu_j \equiv \mu_{pj} = - \frac{\partial v_{pj}}{\partial v_{Gj}} \quad . \quad (\text{III-16})$$

The interaction of electrode i with device j is characterized by the relative influence of electrode i compared with grid j or

$$\frac{\mu_j}{\mu_{ij}} \quad .$$

If a device has two electrodes, a and b , it is said to have 1% interaction with device 1 if

$$\mu_1 \left(\frac{1}{\mu_{a1}} + \frac{1}{\mu_{b1}} \right) = 0.01 \quad . \quad (\text{III-17})$$

The electrode μ 's that affect the gain of the basic $\mu/2$ gain stage are shown in Fig. III-17. In order to simplify the gain equation, the μ 's of the anode shield and cathode shield can be combined into a single μ , i.e.,

$$\frac{1}{\mu_{S21}} \equiv \frac{1}{\mu_{AS21}} + \frac{1}{\mu_{KS21}} \quad , \quad (\text{III-18})$$

$$\frac{1}{\mu_{S12}} \equiv \frac{1}{\mu_{AS12}} + \frac{1}{\mu_{KS12}} \quad . \quad (\text{III-19})$$

Fig. III-17. Basic TIC gain stage showing device interactions that affect the voltage gain. T1 is the gain stage and T2 is the load device.

A number of device arrays were fabricated and the interelectrode μ 's were measured. The devices were operated in a bell jar on the vacuum system because the bell jar could accommodate up to 26 connections to the device (the header for the vacuum package has only 11 pins). The disadvantage of leaving the devices on the vacuum system is the short device lifetime of one or two days.* Once the device was activated and aged enough to stabilize its characteristics, there was not enough time remaining to make all the measurements desired.

The arrays fabricated and tested are listed below.

- A. 4-device array, 50-mil anode-cathode spacing, 7 cathode stripes
- B. 4-device array, 40-mil anode-cathode spacing, 3 cathode stripes
- C. 4-device array, 25-mil anode-cathode spacing, 7 cathode stripes
- D. 2 devices separated by 120 mils, 25-mil anode-cathode spacing, single cathode stripe

Device array A was tested as a basic gain stage (gain device and load device as shown in Fig. III-17). The following configurations of the gain and load devices were tested to determine how device location and orientation affect device interactions (devices a, b, c, and d are identified in Fig. III-16).

1. Adjacent devices (maximum interaction), load device outside (sees less ground plane, μ_{G2} larger)
a = load device, d = gain device
2. Adjacent devices (maximum interaction), load device inside (sees more ground plane, μ_{G2} smaller, gain less than configuration 1)
d = load device, a = gain device
3. Devices end-to-end, load device outside (less interaction than configurations 1 and 2)
a = load device, b = gain device
4. Devices end-to-end, load device inside (lower μ_{G2} , lower gain than configuration 3)
d = load device, c = gain device
5. Diagonal devices, load device outside (the least interaction)
a = load device, c = gain device

*This is because of the large volume of the vacuum system compared with a package. In a practical sense, the vacuum system looks like an infinite source of water that slowly poisons the cathode, as described in a later section.

6. Diagonal devices, load device inside

d = load device, b = gain device

The measured values of the interelectrode μ 's shown in Fig. III-17 are given in Table III-1 for the six configurations. In addition, the calculated voltage gain G_v and the gain normalized to $\mu/2$, $G_v/(\mu/2)$, are given (array A did not live long enough in the bell jar to measure the gain of all configurations). Since the basic gain stage would have a voltage gain of $\mu/2$ without interaction, the value of $G_v/(\mu/2)$ is a measure of the degree of interaction for each configuration. Note that, as expected, adjacent devices have the most interaction, end-to-end devices have less, and diagonal devices have the least interaction.

TABLE III-1
INTERACTIONS FOR 4-DEVICE ARRAY A
(device $\mu = 50$)

Config- uration	μ_{G2}	μ_{AS21}	μ_{KS21}	μ_{AS12}	μ_{KS12}	μ_{P21}	G_v	$G_v/(\mu/2)$
1	83	238	366	218	344	1130	14.8	0.592
2	61	218	344	238	366	1100	13.9	0.556
3	83	418	1640	396	1530	1730	17.0	0.680
4	61	522	366	516	360	728	14.9	0.596
5	83	2200	3220	3700	2380	>5000	18.7	0.748
6	61	4160	2460	2480	2940	>5000	17.3	0.692

Table III-2 compares interactions of the four different arrays. A comparison of device test structures A and C shows that smaller anode-cathode spacing reduces interaction (and reduces device gain). However, array B with 40-mil spacing has even lower interactions (and higher gain) than array C with 25-mil spacing. This is because the cathode width of array B (3 stripes) is less than that of array C (7 stripes). For a given spacing, a narrower cathode reduces the interactions because there is less cathode area to interact with. The gain of the widely spaced array D is 93% of $\mu/2$. This gain reduction is almost entirely due to the effects of the ground shield rather than device-to-device interactions.

TABLE III-2

BASIC GAIN STAGE INTERACTIONS OF DIFFERENT DEVICE ARRAYS
 (Arrays A, B, and C use two devices placed end-to-end.
 Array D uses two adjacent devices spaced 120 mils apart.)

Device	μ	μ_{G2}	μ_{AS21}	μ_{KS21}	μ_{AS12}	μ_{KS12}	μ_{P21}	G_v	$G_v/(\mu/2)$
A	50	61	522	366	516	360	728	14.9	0.596
B	35	83	860	628	814	700	1308	13.3	0.760
C	23	64	798	654	730	574	1254	9.2	0.800
D	25	188	30 000	1428	25 000	25 000	>30 000	11.6	0.929

Finally, the two-dimensional Laplace code was used to calculate inter-electrode μ 's. Because the code is two-dimensional, the results are accurate only for electrodes with a large length-to-width ratio. As can be seen from Fig. III-16, this is reasonable only for interactions between adjacent devices (a and d or b and c). Calculated and measured values for adjacent devices with a 50-mil anode-to-cathode spacing are given in Table III-3 as well as calculated values for 40-, 30-, and 20-mil spacing. The agreement between measured and calculated values is quite good. It is also apparent from Table III-3 that, as the anode-cathode spacing is decreased, the degree of isolation improves while the voltage gain decreases.

TABLE III-3

INTERELECTRODE μ 's FOR DIFFERENT ANODE-CATHODE SPACING

	Anode-Cathode Spacing (mils)				
	50 <u>Meas</u>	50 <u>Calc</u>	40 <u>Calc</u>	30 <u>Calc</u>	20 <u>Calc</u>
μ	50	55	39	25	14
μ_{AS11}	61	56	47	41	39
μ_{KS11}	12	10	11	12	14
μ_{AS21}	218	246	333	573	1888
μ_{KS21}	344	323	391	610	1890
μ_{P21}	1098	935	1675	4628	27 400

3. Projected Level of Integration - Current Technology As was pointed out in the March 1982 proposal, an integration level of 1000 devices/in² can be obtained with less than 1% interaction between adjacent devices. The analysis at that time assumed vertical devices with a 1.5- x 10-mil cathode and a cathode-anode spacing of 20 mils. However, a number of design tradeoffs and considerations are involved that merit a more thorough examination. For example, it was pointed out in Section III.D.2 that decreasing the anode-cathode spacing essentially trades gain for isolation. Decreasing cathode width while maintaining other electrode dimensions increases device gain and maintains about the same degree of isolation. Decreasing the size of the anode and cathode shields or returning them to a constant potential (rather than the cathode potential) increases isolation and can maintain device gain (depending on nearby electrode potentials).

Because of the tradeoffs, a number of device configurations were analyzed with the 2-D Laplace code. The results of Section III.D.2 indicate that the results should be good for interactions between adjacent devices but of course, a 3-D code is required to obtain interactions between diagonal or end-to-end devices.

The basic structure analyzed is shown in Fig. III-18. The interactions between the electrodes of device 2 on the right and device 1 on the left are calculated. It is assumed that all of the device on the right is at signal potential; i.e., grid, cathode, cathode shield, anode, and anode shield are all at signal potential. If the shields are connected to a constant potential, the effective device width (for signal analysis purposes) is reduced and the interaction is reduced. For generality, the interactions will be calculated without regard to how the devices are interconnected. However, it should be noted that the relative importance of the interactions is determined by the way in which the devices are connected. For example, if the anode and cathode shields of device 2 are returned to the cathode of device 2, and the anode of device 1 is connected to the cathode of device 2 (as in the basic gain stage) or the grid of device 2 (as in cascaded gain stages), then the interaction from the cathode, grid, and shields of device 2 to device 1 is negative feedback. That is, the effect of this interaction is to reduce the gain of device 1, as shown by the analysis of the basic gain stage in Section III.D.1. (The measured device-to-device interactions are over 6%, which would have reduced the

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gain from 11.5 to 10.8. However, feedback from ground shield to load device further reduced the gain to 9.2.)

For the structure of Fig. III-18, a nominal device was assumed to have the dimensions given in Table III-4. Then S_{KK} was varied for the nominal device and for different values of W_K , W_{KS} , and S_{AK} . Table III-5 shows some of the results for the nominal S_{KK} of 40 mils. The percent interaction is calculated from

$$\text{interaction} = 100 \frac{\mu}{\mu_S} \text{ percent} , \quad (\text{III-20})$$

where

$$\frac{1}{\mu_S} = \frac{1}{\mu_{SB}} + \frac{1}{\mu_{ST}} . \quad (\text{III-21})$$

TABLE III-4

NOMINAL DEVICE DIMENSIONS IN MILS

Cathode width	W_K	1.0
Grid width	W_G	1.0
Cathode shield width	W_{KS}	2.8
Shield spacing	S_S	1.0
Grid-cathode spacing	S_{GK}	0.2
Device width	W_D	11.0
Cathode-cathode spacing	S_{KK}	40
Anode-cathode spacing	S_{AK}	30

TABLE III-5

SUMMARY OF ISOLATION CALCULATIONS FOR $S_{KK} = 40$ mils

$\underline{W_K}$	$\underline{S_{AK}}$	$\underline{W_D}$	$\underline{\mu}$	<u>Percent Interaction</u>
1	30	11	28	6.3
0.5	30	11	40	6.4
1	30	13	27	7.2
1	30	11	28	6.3
1	30	9	28	5.5
1	30	7	28	4.4
1	30	3.4	28	2.6
1	20	11	18	0.1
1	30	11	28	6.3
1	40	11	37	15

From Table III-5, it can be seen that reducing the cathode width results in a substantial increase in voltage gain with no increase in interaction (i.e., μ_S increased by the same factor as μ). Reducing the device width by reducing the anode and cathode shield widths reduces device interaction. For $W_D = 3.4$, which corresponds to no anode shield or cathode shield (or shields connected to a constant potential), the interaction has been reduced from 7.2% to 2.6%. This may well be the most common case because it corresponds to a grounded cathode stage. Further, it may be appropriate to connect most of the shields to a fixed potential. Finally, Table III-5 shows clearly that reducing the anode-to-cathode spacing amounts to trading gain for isolation.

Figures III-19 and -20 show the isolation μ as a function of cathode-cathode spacing for varying device widths and varying anode-cathode spacing, while Figs. III-21 and -22 show the corresponding percent interaction. Figures III-21(a) and -22(a) are appropriate for digital circuit interactions and most linear circuit interactions, while the expanded scales of Figs. III-21(b) and -22(b) are appropriate for critical interactions in linear circuits.

The end-to-end device interactions cannot be calculated with the 2-D Laplace code; however, Fig. III-16 and Table III-1 in Section III.D.2 indicate that, for the end-to-end device, isolation is higher than for adjacent devices even though the end-to-end spacing is about half that of the adjacent devices.

Fig. III-19. Isolation μ [$\mu_s = (\mu_{SB}\mu_{ST})/(\mu_{SB} + \mu_{ST})$] for varying device widths (W_D).

Fig. III-20. Isolation μ for varying anode-to-cathode spacings.

(a)

(b)

Fig. III-21. Percent interaction for different device widths.

(a)

(b)

Fig. III-22. Percent interaction for different anode-to-cathode spacings.

This isolation would be substantially higher if the cathodes were reduced from seven 1.5-mil stripes to one 1-mil stripe, a 10.5:1 reduction in the length of the edge. If a 10-mil separation adequately isolates end-to-end devices and if the cathode is 10 mils long, then $S_{KK} = 50$ results in 1000 devices/in².

Table III-6 lists the gain, percent interaction, and level of integration for some of the configurations. With a 10-mil cathode stripe, 20-mil anode-cathode separation allows 1670 devices/in² for 5.4% interaction and 1250 devices/in² for 1% interaction, but at reduced gain. An anode-cathode spacing of 30 mils with the nominal device provides improved gain at 1250 devices/in² but increases the interaction to 6.3%. An interesting configuration would be a 0.5-mil-wide cathode and a 20-mil anode-cathode spacing. The 0.5-mil cathode would improve the gain, and the 20-mil anode-cathode spacing would provide a high degree of isolation.

TABLE III-6

GAIN, PERCENT INTERACTION, AND LEVEL OF INTEGRATION FOR SEVERAL
DEVICE CONFIGURATIONS

<u>Cathode Length^a</u>	<u>S_{AK}</u>	<u>μ</u>	<u>W_D</u>	<u>S_{KK}</u>	<u>Percent Interaction</u>	<u>Devices/in²</u>
10	40	37	11	50	6.5	1000
5	40	37	11	50	6.5	2000
10	30	28	11	40	6.3	1250
5	30	28	11	40	6.3	2500
10	30	28	3.4	30	8.7	1670
5	30	28	3.4	30	8.7	3330
10	30	28	3.4	50	0.5	1000
5	30	28	3.4	50	0.5	2000
10	20	18	11	30	5.4	1670
5	20	18	11	30	5.4	3330
10	20	18	11	40	1.0	1250
5	20	18	11	40	1.0	2500

^a10-mil cathode and 10-mil isolation shield or 5-mil cathode and 5-mil isolation shield.

4. Design/Fabrication of an Integrated Circuit

a. Initial Design of an Integrated Flip-Flop The flip-flop shown in Fig. III-23 was chosen as the first completely integrated circuit to be designed and fabricated in the TIC technology. As can be seen in Fig. III-23, this circuit uses a total of 10 devices; the layout has been arranged for expediency (See Section 4.b of this section) to separate the devices enough to minimize interactions. Figure III-24 shows the circuit broken down into its basic circuit components (a mask for manufacturing the circuit in this fashion was created first in order to test each of the independent circuit elements).

The test circuit then consists of two gain stages (T1, T2 and T6, T7) and two level shifters (T3, T4, T5 and T8, T9, T10) that can be connected in a number of ways. For example, a gain stage can be connected to a level shift to provide a logic inverter whose dc output level is compatible with the input of a similar stage as is required for logic circuits and dc-coupled amplifiers. When two inverters are cascaded with the output of the second connected to the input of the first, a simple flip-flop is formed.

The level shift circuit has a gain of approximately 1/2 and incorporates a cathode follower in order to prevent loading of the gain stage by the level-shift circuit. For simplicity, no provisions are included for triggering or for logic input, and no attempt has been made to optimize device or circuit performance. The dc levels at the input of each inverter are approximately +1 and -3 V.

Figures III-25 and -26 are photographs of the masks for the two flip-flop substrates. The circuit has been laid out so that all the points indicated in Fig. III-24 can be brought out or so that some can be connected internally. If desired, the flip-flop can be completely connected internally. The options are obtained by selectively opening some of the metal interconnections on the masks; examples can be seen in Figs. III-25 and -26.

Several of these circuits have been fabricated and tested as gain stages, logic inverters, and flip-flops. Figure III-27 shows the output waveform of a flip-flop when it is triggered by externally generated pulses (this circuit was operated in a bell jar, and the long external connections required introduced substantial capacitance, which caused the slow speed shown in the figure). Figure III-28 is a photograph showing both flip-flop substrates.

The exercise of designing and testing the circuit proved to be enlightening in a number of ways.

Fig. III-23. Circuit diagram of the fully interconnected flip-flop.

Fig. III-24. Flip-flop circuit diagram showing basic circuit components.

Fig. III-25. Mask for blue substrate.

Fig. III-26. Mask for red substrate.

Fig. III-27. Flip-flop waveform.

Fig. III-28. Two flip-flop substrates.

1. The circuit worked as predicted.
2. The improved processing yielded leakages and spurious emission levels in the circuit that were immeasurably low.
3. The interactions from the shield to the devices had to be measured experimentally (the two-dimensional computer simulation, which works well for long, thin structures, was found to be difficult to apply to the complex geometries of an actual circuit).
4. The level shift stage as created gives up over half of the voltage gain; therefore, devices or circuits that behave like current sources will ultimately be required to increase the level shift gain to nearly 1, or devices that operate at a high positive grid voltage could be used either for the basic gain stage or as level-shifting cathode followers.

b. An Improved Flip-Flop Layout Because an adequate layout and mask generation facility was not readily available,* the flip-flop masks had to be created in a rather cumbersome manner. Device masks with the critical 0.3-mil grid-cathode spacing have been manufactured previously by a mask house. These are large devices with seven cathode stripes, each 1.5 x 55 mils. A method had also been devised whereby devices could be placed in any of 24 fixed locations. Then the devices could be interconnected by generating metal artwork on an available low-precision system (4-mil lines and spaces). Because of the unnecessarily large devices and the lack of flexibility in placing the devices, the test flip-flop consumes much more area than necessary; the level of integration corresponds to about 50 devices/in² of active area.

Because of the above restrictions, the test flip-flop gives no real indication of the attainable level of integration. The analysis discussed in Section III.D.3 predicts 1000 devices/in² with less than 1% interaction between adjacent devices. In order to partially verify this, the flip-flop was redesigned using the current TIC technology but with redesigned devices, flexible placement, and 1-mil lines and spaces for metal interconnect.

The redesigned device has a single cathode stripe, and its basic configuration is shown in Fig. III-29. The cathode is 0.8 mils wide, the grid is

*The cost of having this work done by an outside mask house was considered beyond the means of the program.

Fig. III-29. Redesign of the cathode-grid-cathode shield structure for the improved flip-flop layout.

0.9 mils, and the grid-cathode spacing is 0.2 mils. The total device width W_D is 6 mils including shield.*

For a given overall device length L_D , the cathode length L_K and grid length L_G are

$$L_K = L_D - 4.1 \quad \text{and} \quad (\text{III-22})$$

$$L_G = L_D - 3 \quad . \quad (\text{III-23})$$

The length of the corresponding anode L_A and width of the anode W_A are

$$L_A = L_G \quad \text{and} \quad (\text{III-24})$$

$$W_A = 3 \quad , \quad (\text{III-25})$$

and the anode shield is identical to the cathode shield.

For the flip-flop, a device length of 24 mils is used. The grid length, cathode length, and cathode area A_K are

$$\begin{aligned} L_G &= 21 \text{ mils,} \\ L_K &= 19.9 \text{ mils, and} \\ A_K &= 15.9 \text{ mils}^2. \end{aligned}$$

While this device has not been fabricated and tested because of the lack of artwork facilities, it is believed to be a conservative design for the following reasons.

1. The current processing technology has demonstrated cathode widths of 0.5 mil or less; 0.8 mil is, therefore, easily attainable (0.5-mil cathodes have been successfully delineated but not tested in devices).
2. A number of single cathode stripe devices have been fabricated (using the standard device but coating only 1 cathode stripe) and tested. The characteristics of these devices are basically the

*The 1-mil-wide cathode shield is to provide some isolation between the cathode and ground shield, that is, to reduce the biasing effect of the ground shield on the cathode. Additional shielding by the ground shield is required to reduce device-to-device interactions.

same as the multicathode stripe devices, but they operate at a lower current level. The single stripe devices have a cathode area of $1.5 \times 55 = 82.5 \text{ mil}^2$.

3. Diodes have been fabricated with a cathode area of only 25 mil^2 . These diodes operate at current levels sufficiently high to drive external circuitry. Even smaller cathodes can be used to drive off-chip; if the device drives only other on-chip devices, the cathode could be much smaller.

A possible flip-flop layout is shown in Fig. III-30; this layout permits the devices to be interconnected as a flip-flop without crossovers. The dotted area would maintain as much space between adjacent flip-flops as that maintained between adjacent devices. The area enclosed by the dotted rectangle is 9180 mils^2 , which corresponds to $1089 \text{ devices/in}^2$.

The analysis discussed in Section III.D.3 used a cathode-to-cathode spacing to cathode width ratio of 50:1 to maintain interaction between adjacent devices at less than 1% and a cathode length of 10 mils. The layout of Fig. III-30 has a cathode spacing to cathode width ratio of 37.5, resulting in more interaction between adjacent devices, which is allowable for a digital circuit. On the other hand, the devices used for the flip-flop layout have a cathode length of 19.9 mils rather than 10 mils. It is projected that devices with $0.5\text{-mil} \times 10\text{-mil}$ cathodes could easily be fabricated; use of these devices would further reduce the total flip-flop area substantially.

5. Level Shifting in a Single Device (a feasibility experiment)

The basic inverter circuit used for the TIC flip-flop requires five devices—two for the basic gain circuit and three to level shift its output. The dc transfer characteristic of the basic gain stage is shown in Fig. III-31(a). because the low output of the gain stage is over 40 V and because the gain stage requires a negative voltage to turn it off, the output of the gain stage must be shifted downward to provide an output that is dc-compatible with the input of a similar stage. The output of the complete inverter is shown by the solid curve in Fig. III-31(b). If the inverter is driving a similar stage, the load stage draws grid current at about 2.3 V. This limits the positive output of the inverter and is shown by the dashed curve of Fig. III-31(b). It is evident that the output of the complete inverter is compatible with the input of a similar inverter, but the level shift circuit adds three more devices and reduces both the gain and logic swing of the inverter.

Fig. III-30. Improved flip-flop layout. Total area is 9180 mils² yielding 1089 devices/in².

(a)

(b)

Fig. III-31. DC transfer characteristics of the (a) basic gain stage and (b) complete inverter.

Fig. III-32. Proposed level shift device.

One way to reduce the inverter device count and to perhaps improve the gain and logic swing is to introduce an additional set of grids in the gain device as shown in Fig. III-32. If a negative voltage is applied to the bias grid, the device could be cut off with a positive grid voltage. A higher grid voltage would then turn the device on. The bias grid is closer to the cathode in order to prevent the grid from drawing grid current with a positive bias.

An existent test device was modified as shown in Fig. III-33 to test this concept. Only the center cathode stripe had cathode coating. The two innermost 1-mil grids were used as bias grids, and the next two cathode stripes were used as grids. The remaining grids and cathodes were shorted together to form the shield. This device would be expected to have low gain because the 1-mil bias grids and 0.3-mil spacing force the grids to be 1.6 mils away from the cathode.

The transfer characteristics of this device with a 1-M Ω resistive load and a 25-V supply are shown in Fig. III-34. As can be seen, the output is compatible with the input of a similar device (the operating points are circled); the logic swing is larger than that of the flip-flop inverter; and the gain is low because of large grid-cathode separation. This device shows feasibility for an improved inverter with a device count of only 2. However, more suitable devices with narrower bias grids and higher gain need to be tested with active loads while driving similar stages.

It is also expected that such a device could be used as a cathode follower, which operates at a large positive grid voltage. Using such a device may obviate the need for the diodes used in level-shifting diodes, such as those employed in the test flip-flop.

6. Current Source Devices. Often in the design of circuits, it is useful to have a device whose current is virtually independent of anode voltage. Such a device is referred to as a current source and is useful in such circuits as active loads, level shifters, and differential amplifiers. As was observed in the design of the test flip-flop, one-half of the voltage gain was lost in bringing the output voltage back to ground through a string of diodes. Professors Douglas Hamilton and William Kerwin and graduate students Lazaro Hong and Dan Schoenerman at the University of Arizona (U of A) under sponsorship of the National Science Foundation have been investigating advanced TIC device morphologies. This program was developed in cooperation with Los Alamos and has

Fig. III-33. Level shift test device.

Fig. III-34. Transfer characteristics of the level shift test device.

been directed at augmenting the Los Alamos technology base. One structure proposed by Hong and being investigated at the U of A is the current source device as shown in Fig. III-35. This structure relies on several principles for operation.

1. To achieve current source operation, the field from the anode as seen by the cathode must be small so that influence of changing anode voltage is small.
2. As a result of 1, the electron transport from cathode to anode must be facilitated by fields induced by electrodes other than the anode.
3. Lens structures can be designed that provide the fields necessary to accomplish 2.

Figure III-36 shows a computer-generated map of constant field lines for a device with lens 2 at +100 V and lens 1 at -100 V, grids at -1 V, and anode at +10 V. Note that the lens structure creates the desired electron transport.

Figure III-37 is an example of measured characteristics of a test device. The slope of the characteristics is primarily due to parasitic leakage present in devices fabricated at the U of A.

These devices show great promise as current sources, although much work remains to be done. Principally, because the device relies on the operation of the lens structure, evaluations must be made of the effects on the device operation as the cathode voltage is varied with respect to the fixed lens potentials. Also, a general set of design rules for creating a current source with desired characteristics must be developed.

However, the U of A structure shows promise for enhancing the TIC capability and should be investigated further as part of any continuing program.

E. Conclusions

The work performed on this phase of the project (augmented with DOE, Basic Energy Sciences support and NSF support at the University of Arizona) demonstrates that integrated circuits using the TIC technology are possible. Test circuits performed as expected, and improved processes were developed that greatly reduced parasitic currents.

This work confirms previous analyses that integrated circuits with device counts of between 1000 and $10,000/\text{in}^2$ are likely in the near term and that devices with improved functionality (current sources, level shift devices) are likely in the future. However, the experience also pointed out the need

Fig. III-35. Monoplanar TIC current source developed and tested at the University of Arizona.

Fig. III-36. Constant field lines and electron trajectories for the monoplanar current source.

Fig. III-37. Measured response of the monoplanar current source.

for better 3-D analysis Laplace codes in order to better predict performance and the need for better CAD tools to improve turnaround on masks.

F. Recommendations

1. In any continuation of TIC technology development, a substantial investment is required in circuit technology.
2. CAD support tools should be used and improved 3-D Laplace codes should be developed.
3. Experiments with advanced device morphologies should be continued to improve functionality per device.
4. Enhanced processing techniques should be investigated including smaller lithography (both cathode and line), improved cathodes (higher current density at long life), resistors, capacitors, and metalization crossovers.

IV. POWER REQUIREMENTS

A. Statement of Work from Proposal (March 1982)

"Present test devices and circuits are fabricated on substrates having a heater element on the reverse side of the substrate. Two substrates are presently packaged in an evacuated glass envelope (Fig. IV-1). (Metal packages are used for high-temperature tests.) Present heater power in the glass envelope is 15 W per 0.75-in.-diam substrate pair, with the substrates at 750°C and the envelope at 25°C ambient. No heat radiation shields are used, and no attempt has been made to minimize conductive losses through bonding wires and substrate supports.

"Calculations show that more than an order of magnitude reduction can be achieved by using a package designed with appropriate heat radiation shields, by reducing conduction losses through use of thinner wires and by packaging many substrates in the same envelope. Specifically, analysis shows that for eleven 0.75-in.-diam substrate pairs in the same envelope with appropriate shields between substrate stack and envelope, the power required would be approximately 1.14 W/substrate pair (a similar result can be achieved by using a single pair of 2-in.-diam wafers). If a nominal level of integration (e.g., 1000 devices/in²) is achieved, there would be 4859 devices in the package, each requiring 2.58 mW of heater power per device. The total heater power for the

4859 devices would be 12.54 W. This assumes no power dissipation in the devices; in reality, device dissipation would allow further reduction of heater power. Therefore, a package containing several substrates with heaters and heat shields will be designed and fabricated. Heater power required to maintain the substrates at 750°C will be measured for several different envelope temperatures. Results will verify calculations and will provide direction for future package development."

B. Theoretical Analysis and Experimental Results

Two mechanisms account for the total internal heat loss. The first is direct thermal radiation from the sapphire substrates according to the Stefan-Boltzmann law:

$$P_1 = e A \sigma (T_1^4 - T_2^4) , \quad (IV-1)$$

where P_1 is the radiated power in W, e is the emissivity of sapphire at T_1 , A is the area of the sapphire in cm^2 , σ is the Boltzmann constant ($5.7 \times 10^{-12} \text{ W/cm}^2 \text{ K}^4$), T_1 is the temperature of the sapphire (K), and T_2 is the temperature of the outer envelope (K). The second mechanism is conduction through the support wires and leads:

$$P_2 = k (A_1/\ell) \Delta T , \quad (IV-2)$$

where P_2 is the power conducted in W, k is the thermal conductivity ($0.91 \text{ W/cm}^\circ\text{C}$), A_1 is the cross-section area of the lead (cm^2), ℓ is the lead length, and ΔT is the temperature differential ($^\circ\text{C}$).

Since the sapphire is normally at about 1073 K (800°C), according to Wien's Displacement Law, the peak radiation occurs at

$$\lambda_{\text{max}} T = 2880 \text{ } \mu\text{m K} \quad (IV-3)$$

or $\lambda_{\text{max}} = 2.68 \text{ } \mu\text{m}$. At this wavelength the glass outer package used for current prototype devices is essentially black and absorbs nearly all the radiation emitted by the sapphire substrates. The sapphire itself has an emissivity of about 0.5 at this temperature. For an area of 6.52 cm^2 including the edges of

the 30-mil-thick sapphire, the total radiation is $P_1 = 0.5 (6.52) (5.7 \times 10^{-12}) (1073^4 - 400^4) = 24 \text{ W}$. When two support leads, four heater leads, and three circuit leads are included, $P_2 = 2 \text{ W}$. The total theoretical heat loss is, therefore, 26 W with the radiation term by far dominant.

Experimentally, the heat loss was initially measured as between 26 and 28.1 W, depending on whether the thermocouple or optical temperature reading was used. The outside envelope temperature was measured at 127°C. At this temperature, using an emissivity of 0.9 for the envelope, an area of 91 cm², and a background temperature of 300 K, the external bulb radiation P_3 is 7.3 W. The rest of the heat loss must be by external conduction and convection. For an approximately uniform surface temperature, this is

$$\theta \approx 60/A^{1/2}, \quad (IV-4)$$

where θ is in °C/W and A is the area in cm². For $A = 91 \text{ cm}^2$, $\theta = 6.3^\circ\text{C/W}$.

Since the net heat loss to be accounted for is $P_1 + P_2 - P_3 = 18.7 \text{ W}$, then the external temperature would theoretically be $6.3 \times 18.7 = 117^\circ\text{C}$ above ambient or 142°C. The actual measured temperature was 127°C.

Next, a similar assembly was built (Fig. IV-2), but the envelope was internally coated with gold (emissivity ≈ 0.05 at 1100 K) to provide a highly reflective surface to reduce the radiative transfer from the sapphire substrates. To allow for the fact that the ends were not coated, an effective envelope emissivity of 0.06 was used. The heat transfer was then approximated to first order by using the analytic equation for heat transfer between two concentric spheres.

$$Q_1 = \frac{e_1 e_2}{e_2 + e_1 (1 - e_2)(r_1/r_2)^2} \sigma (T_1^4 - T_2^4), \quad (IV-5)$$

where

- Q_1 = heat flow, W/cm²,
- e_1 = emissivity of T_1 surface,
- e_2 = emissivity of T_2 surface,
- r_1 = radius of inner sphere, cm,

Fig. IV-1. Clear glass envelope.

Fig. IV-2. Envelope coated with silver (left) and gold (right) to reduce heat loss and power requirements.

r_2 = radius of outer sphere, cm,
 σ = Boltzmann's constant,
 T_1 = inner sphere temperature, and
 T_2 = outer sphere temperature.

An equivalent radius r_1 was found by equating the sphere area to the sapphire area, and an equivalent radius r_2 was found by similarly equating the envelope area to that of a sphere. The result for $T_1 = 1073$ K, $T_2 = 400$ K, $e_1 = 0.5$, $e_2 = 0.06$, $r_1 = 0.72$ cm, and $r_2 = 2.69$ cm was $Q_1 = 2.33$ W/cm² or a power of 15.2 W for a sapphire area of 6.52 cm². When a conduction heat flow of 2 W is included, a total heat loss of 17.2 W is predicted. The optically measured heater power was 18 W while the thermocouple readings indicated 16 W. The measured reduction in heater power was more than 30%, as predicted by analysis.

The next test was the addition of two more sapphire substrates immediately adjacent to and coaxial with the original device substrates. These were gold plated on the inner surface to shield both faces. In addition, the device substrates were now mounted horizontally. In this case, the formula for radiative transfer between parallel planes was used to calculate the heat flow

$$Q_2 = \frac{e_1 e_2}{e_2 + e_1 (1 - e_2)} \sigma (T_1^4 - T_2^4) , \quad (\text{IV-6})$$

where

Q_2 = heat flow, W/cm²,
 e_1 = emissivity of T_1 surface,
 e_2 = emissivity of T_2 surface,
 σ = Boltzmann's constant,
 T_1 = temperature of surface 1 in K, and
 T_2 = temperature of surface 2 in K.

In addition, the temperature of the shields T_s could be calculated because at equilibrium, $Q_2 = Q_3$, where Q_3 is the heat radiated from the shields and is

$$Q_3 = \sigma e_3 (T_s^4 - T_2^4) , \quad (\text{IV-7})$$

where e_3 is the outer sapphire surface emissivity (0.5) and T_2 is the envelope

temperature. This resulted in T_s being 616 K. With this temperature reduction, the total radiation, not including the edges of the shields, was expected to be $Q_3 = 0.5 (5.7 \times 10^{-12})(616^4 - 400^4) \text{ W/cm}^2$. For an area of 6.52 cm^2 , the power radiated was $P_4 = 2.4 \text{ W}$. When we add in the edge and conduction losses, the total heat loss is 7.5 W. The measured power required was 13.9 W. This was a measured improvement over the clear envelope of about 47%, again as predicted by theory. The discrepancy is probably due to the shield being only as large as the device substrates and being spaced away from them. Thus, some surface radiation would not be stopped by the shield.

The next test attempted to simplify the system by using a low-emissivity gold coating on the device substrates themselves. An SiO_2 layer was used to avoid shorting out the heater. The results were excellent while on the vacuum pump, but the system failed as soon as the tube was pinched off because of conduction caused by the gas given off from the sputtered SiO_2 . This experiment showed promise, and a more appropriate insulator material and deposition technique should be investigated as part of any follow-on TIC program.

Another test was made using 0.018-in.-thick, 1-in.-diam nickel disks that were gold plated on the inside in place of the two extra sapphire wafers. The result was a total power of 12.1 W. There were still edge losses and the nickel was not highly polished so that the gold plating was not entirely effective. A high-emissivity coating is also required on the outside surface of the nickel.

Future tests should contain two end heaters and shields but with a stack of five device substrates in between and a gold-plated envelope. Temperature will be measured near the center of the stack and on the heater substrate.

C. Conclusions

The total power required for the clear envelope and unshielded device substrates is adequately explained theoretically. The effect of reflective shielding internally and of added shields outside the sapphire substrates is also reasonably in accord with the theory, allowing for unavoidable losses in the experimental arrangement. The total power was reduced from 24-28 W unshielded to 12.1 W with the best heat shield. From these results it appears practical that, with additional work, the total power required can be reduced to below 10 W without adding any additional shields. These results verify the previous (March 1982 proposal) prediction that, at the level of integration of

1000 devices/in² with multiple substrates, 2.5 mW of heater power per device will be achievable. Because the power per substrate stays constant, independent of the number of devices, at 10,000 devices/in², the heater power per device would be 0.25 mW.

D. Recommendations

1. Work should be continued to solve the problems of placing an insulating material over the heater without trapping gas. Then a low-emissivity coating can be applied to the insulating layer. This coating must be smooth to better than 1 μm .

2. For long-term use at high temperature, the vapor pressure of gold is too high. A literature search shows that rhodium is satisfactory. After this heater coating has been worked out, an additional nickel shield could be added with an internal coating of rhodium and an external coating of oxide for high emissivity. Hafnium oxide is excellent, but nickel oxide is reasonably good and could be formed on the nickel after the rhodium plating on the other side. The rhodium and the oxide layer should be 3 μm thick. Also, the edges of the device substrates need to be covered with 3 μm of rhodium.

3. After the materials/processes supporting the approach outlined above are completed and tested, a complete TIC package should be designed and tested. This package should include not only thermal design but also shock and vibration features.

V. DEVICE SPEED/BANDWIDTH

A. Statement of Work from Proposal (March 1982)

"A common figure of merit for comparing device speed is the gain-bandwidth product (GBP) that is customarily characterized as the ratio of the transconductance to an equivalent load capacitance. Figure V-1 shows a general case applicable for any three-terminal electronic device. Here the equivalent capacitance C_{eq} is the sum of the output capacitance of the device and the input capacitance of the following device, together with any parasitic capacitance. Therefore, the GBP is

$$\text{GBP} = g_m / 2\pi C_{eq} \quad , \quad (\text{V-1})$$

where g_m is the transconductance of the device (recall, g_m is a function of the current at which the device is operated as well as the device geometry). For present TIC devices, the dominant capacitance is the grid-cathode capacitance because of the proximity of those two electrodes and because the sapphire substrate has a relative dielectric constant of 10. The GBP was not important for the applications previously addressed, so it has not been measured. However, the following data are available.

- o Using measured values of g_m and calculated values of the grid-cathode capacitance, an estimate of the GBP of present devices has been shown to be 30 MHz.
- o A sinusoidal oscillator was fabricated with an oscillation frequency of 5 MHz and was tested at 500°C.

"Measurements of GBP will be made on a number of devices of different geometries to determine the limits of the present technology and how these limits are related to device geometry and processing constraints. These measurements will also be compared with theoretical analyses to evaluate the capability of the analytical methods for predicting device performance."

B. Modifications to the Statement of Work

Because of the number of technical issues to be addressed within the scope of the program and because of the time and cost involved in generating new masks for test structures, it was decided that an analytical approach to the bandwidth/speed issue would be taken in order to bound the expected performance range and highlight parametric relationships. A detailed computer analysis to more accurately evaluate space-charge-limited device performance and a thorough measurement and characterization effort should be undertaken as part of any continued TIC development effort.

C. Theoretical Analysis of GBP

Scaling of TIC devices should improve the GBP as should operating the devices at the highest possible current density. For purposes of analysis, the geometry assumed for the device is shown in Fig. V-2. As can be seen, both cathode and anode are raised, permitting emission from the side of the cathode. It is assumed that means are available to prevent emission from all cathode surfaces except the side facing the anode. If necessary, a shield plane can be located some distance above the substrate.

The following assumptions and approximations are then made. Current is assumed to be space-charge limited. Photolithography imposes a minimum feature size limitation α . All current flow is assumed to be one dimensional between the cathode and anode. The device can be analyzed as though it were a parallel-plane triode with a grid located some effective distance from the cathode and normal to the current flow. The effective distance of the grid from the cathode is approximately α . No fringing effects contribute either to interelectrode capacitance or to the amplification factor μ . Spangenberg's equation⁵ for current in a parallel-plane triode applies, subject to the above assumptions. Wolfe's results for capacitance⁶ are used where applicable. Work functions are neglected. (In a practical sense, the work functions offset the bias voltages of the grid and anode relation to the cathode by the difference between the work function of the metal and that of the cathode.)

If the dimensional dependence of perveance is taken into account, the current in a parallel-plane triode⁵ can be written as

$$i_P = \frac{A_k b (v_G + v_P/\mu)^{3/2}}{(\alpha^{4/3} + d^{4/3}/\mu)^{3/2}}, \quad (V-2)$$

where

- A_k = cathode area,
- $b = 2.34 \times 10^{-6}$,
- v_G = grid-cathode voltage,
- v_P = anode-cathode voltage, and
- d = distance from anode to cathode.

From this, the transconductance can be determined by

$$g_m \equiv \frac{\partial i_P}{\partial v_G} = \frac{3}{2} A_k b \frac{(v_G + \frac{v_P}{\mu})^{1/2}}{(\alpha^{4/3} + \frac{d^{4/3}}{\mu})^{3/2}}. \quad (V-3)$$

This can be written in terms of the current density J as

$$g_m = \frac{1.5 A_k b^{2/3} J^{1/3}}{(\alpha^{4/3} + d^{4/3}/\mu)} \quad (V-4)$$

Formulation in terms of J is useful because it may be desirable to operate the cathode so that some acceptable $J_{\max}$ is maintained. By substituting $A_k = \alpha L_k$, where L_k is the length of the cathode stripe and $d = 3\alpha$,

$$g_m = \frac{2.63 \times 10^{-4} L_k J^{1/3}}{\alpha^{1/3} (1 + 4.33/\mu)} \quad (V-5)$$

Wolfe's results,⁶ with suitable approximations, show that the capacitances per unit length as defined in Fig. V-3 are $C_{\lambda 6} \approx 0.688\epsilon_0$, $C_{\lambda 7} \approx 0.780\epsilon_0\epsilon$, and the grid-cathode capacitance, C_{eq} , for $\epsilon = 10$ is

$$C_{eq} \approx (C_{\lambda 6} + C_{\lambda 7}) L_k = 7.51 \times 10^{-13} L_k \text{ farads} \quad (V-6)$$

where L_k is now in centimeters.

With the above results for g_m and C_{eq} , the GBP can be written as

$$GBP = \frac{5.58 \times 10^7 J_{\max}^{1/3}}{\alpha^{1/3} (1 + 4.33/\mu)} \quad (V-7)$$

where J is in A/cm^2 and α is in cm. For $J_{\max} = 0.200 A/cm^2$, $\alpha = 10^{-4}$ cm and $\mu = 3$; the GBP is 288 MHz. This is, of course, a low μ case. If $\mu = 30$ and the other values are unchanged, the GBP is 614 MHz. As expected, the GBP is a weak function of μ .

By solving Eq. (V-3) for $(v_G + v_P/\mu)$, setting $v_G = 0$, and inserting the appropriate relationship for μ , an anode voltage $v_P = 66$ mV is required to obtain $0.200 A/cm^2$ for $n = 1$ ($\mu = 3$).

From Spangenberg,⁴ the transit time for electrons to traverse the region from cathode to anode is approximated by

$$\tau_t = 3 d/v_P \quad (V-8)$$

where v_p is the velocity of electrons at the anode. If the initial velocity is zero, then from energy considerations

$$v_p = [(2e/m)V_p]^{1/2} . \quad (V-9)$$

For $\alpha = 10^{-4}$ cm and $V_p = 1$ V, τ_t is found to be 15 ps. Preliminary computer modeling including actual electron trajectories, space charge, and geometry indicates a transit time of approximately 34 ps. One set of computer simulation results is shown in Fig. V-4. (The transit time from the simulation is a factor of 2 higher than the idealized theoretical problem but lends credence to the assumptions made. As will be shown in the following, transit time does not represent a general limitation in small TIC devices.) A 15-ps transit time corresponds roughly to a cutoff frequency of

$$f_t = 2.2/(2 \pi \tau_t) = 23.2 \times 10^9 \text{ Hz} . \quad (V-10)$$

If the grid-cathode leakage sheet resistance ρ_s is $10^9 \Omega/\text{sq}$, the leakage current will be 1 nA/V per unit length. At a cathode current density of 0.200 A/cm^2 , the emission current will be 2 nA per unit length for a cathode height of 1 μm . This underscores the necessity of insuring minimum grid-to-cathode leakage current and operating the cathode at the largest allowable current density.

This theoretical reasoning gives comparative results, indicating the factors on which GBP depends. In Tables V-1 and -2, it is seen that operation at higher anode voltages and, consequently, at large current densities is desirable for a large GBP. It should be noted that TIC cathodes routinely approach current densities of 20 A/cm^2 dc in test devices. Notice that in all cases above, the limitation imposed by transit time is substantially above that imposed by $\mu\text{m}/C$.

Figure V-5 presents data similar to Table V-1 in graphical form.

Fig. V-3. Capacitances in a planar device.

Fig. V-4. Computer simulation showing equipotentials and electron trajectories of the 1- μm theoretical device for the GBP calculation. Cathode is to the left, anode is to the right, grid is along the bottom, and repeller is along the top. Potentials used: cathode 0.0 V, anode 1.0 V, grid 0.01 V, repeller -2.25 V. Electron transit time was 34.2 ps.

Fig. V-5. GBP as a function of feature size.

TABLE V-1

GAIN-BANDWIDTH PRODUCT IN MEGAHERTZ VS DEVICE FEATURE SIZE (α)
AND CURRENT DENSITY (J)

α (μm)	$J = 0.2 \text{ A/cm}^2$		$J = 1 \text{ A/cm}^2$		$J = 10 \text{ A/cm}^2$	
	$\mu = 5$	$\mu = 50$	$\mu = 5$	$\mu = 50$	$\mu = 5$	$\mu = 50$
10,000	17.5	30.0	30.0	51.4	64.6	111
5000	22.1	37.9	37.8	64.7	81.4	139
2500	27.8	47.7	47.6	81.6	103	176
2000	30.0	51.4	51.3	87.9	111	189
1000	37.8	64.7	64.6	111	139	238
500	47.6	81.6	81.4	139	175	300
200	64.6	111	111	189	238	408
100	81.4	139	139	238	300	514
50	103	176	175	300	378	647
20	139	238	238	408	513	879
10	175	300	300	514	646	1107
5	221	379	378	647	814	1395
2	300	514	513	879	1105	1893
1	378	647	646	1107	1392	2385

TABLE V-2

GAIN-BANDWIDTH PRODUCT CALCULATIONS
FOR 1- μm -FEATURE SIZE

V_P (V)	J (A/cm ²)	μ	g_m/L_k ($\mu\text{S/cm}$)	GBP (GHz)	τ_t (ps)	f_t (GHz)
1.000	11.70	3	5289	1.100	15	23.2
1.000	1.16	30	5211	1.100	15	23.2
0.310	0.20	30	2900	0.618	27	13.1
0.066	0.20	3	1363	0.283	58	6.0

D. Enhanced Processing

If a process analogous to a "self-aligned" IC process is developed, the effective spacing between the grid and cathode could be reduced in the manner shown in Fig. V-6. For this case, in which minimum spacing of 0.1 is assumed,

$$g_m = \frac{1.5 b^{2/3} L_k J^{1/3}}{\alpha^{1/3} (0.05 + 1.28/\mu)} \quad (V-11)$$

and

$$C_{eq} = (1.98 + 2.82\epsilon)\epsilon_o L_k \quad (V-12)$$

For $J = 0.200 \text{ A/cm}^2$ and $\alpha = 10^{-4} \text{ cm}$, the GBP is $0.42 \times 10^9 \text{ Hz}$ for $\mu = 3$ and $1.74 \times 10^9 \text{ Hz}$ for $\mu = 30$.

Use of a self-aligned process with smaller grid-cathode spacing would increase the GBP, but not by an order of magnitude. It would, however, significantly increase the leakage current. Operation at the largest allowable cathode current density not only would improve the GBP but also would improve the ratio of cathode current to leakage current.

Table V-2 also shows that g_m is not changed by an order of magnitude for any of the conditions calculated, and it seems evident that refinement of the approximations will not result in drastic alteration of the obtainable g_m . Therefore, to make significant improvement of the GBP by process variations would require a modification that reduces C_{eq} . A more likely approach, however, would be to include grooves in the substrate to reduce the interelectrode capacitance (Fig. V-7). Table V-3 shows the calculated effects on interelectrode capacitance vs depth of groove using the notation in Fig. V-8.

Fig. V-6. Reduction of grid-cathode spacing in self-aligning planar device.

Fig. V-7. Grooved planar device to reduce grid-capacitance cathode.

Fig. V-8. Reference figure for depth of groove vs capacitance calculation.

TABLE V-3

CAPACITANCE OF GROOVED SAPPHIRE NORMALIZED TO UNGROOVED

<u>d (μm)</u>	<u>Grid-Cathode Normalized Capacitance (10-mil-thick sapphire)</u>	<u>Gain-Bandwidth Improvement Factor</u>
no groove	1.0	--
1	0.82	1.22
5	0.58	1.72
10	0.43	2.33
12.7	0.38	2.63
19	0.29	3.45
25.4	0.23	4.35

E. Conclusions

As can be seen from Table V-1, TIC devices with gain-bandwidth products on the order of 100 MHz can be designed with current technology. Higher current densities of 10 A/cm^2 such as those commonly observed in TIC test devices but not characterized for lifetime under those conditions would increase frequency responses of devices achievable with current technology to over 500 MHz. Smaller feature sizes or grooved substrates could be expected to increase these frequencies to gigahertz levels.

F. Recommendations

1. As can be seen from Tables V-1 and V-2 and Fig. V-5, the speed of the devices can be greatly enhanced by running at higher current densities. Therefore, understanding the effects of high current density operation on cathode lifetime is important. A continuation of the characterization described in Section VI.B should be part of any continuing TIC program.

2. Ways of improving the processing and lithography of cathodes should be investigated in order to minimize spacing between grid and cathode.

3. Processing techniques for grooving substrates as part of the process should be investigated (including perhaps the use of different substrate materials).

4. Although Los Alamos has developed and routinely used computer codes to predict the performance of TIC devices, a new code should be developed with adjustable meshing contours to more accurately describe the rapid variation in potential occurring near the cathode of a planar device.

5. A variety of TIC structures should be fabricated and tested to verify the GBW calculations, as described in the Appendix.

6. The models described in the preceding section do not include the cathode dynamics. Thermionic cathodes have been historically observed to provide substantially (sometimes orders of magnitude) more current in the "pulsed" mode or during transient operation. This effect has also been observed in the TICs. TIC cathodes must, therefore, be thoroughly characterized and modeled for transient operation.

VI. LIFE AND RELIABILITY

A. Statement of Work from Proposal (March 1982)

"Devices have been operated continuously with substrates at 750°C and envelopes at 500°C ambient for 13,000 hours. During that time, no degradation of device dc characteristics was observed. After 13,000 hours a pin seal on the package failed and the test was terminated." No further activity in this area was proposed under this program.

B. Experimental Program for Another Sponsor - High Current Density Cathodes

An industrial sponsor of this technology (with interest in a very different set of commercial devices that utilize TIC cathodes and fabrication processes) has requested that Los Alamos investigate life and reliability issues as related to the cathode. The approach to these tests is summarized in this section along with preliminary cathode current data.

Current density is basically a measurement of cathode efficiency at a given temperature. The higher the current density, the larger g_m/C ; or conversely, a smaller cathode area can produce equivalent g_m with a corresponding reduction in capacitance and increase in packing density. Temperature might also be lowered for a high current density cathode, reducing heater power requirements and promoting increased lifetime. Conventional receiving tubes were designed to operate at 100 mA/cm^2 to achieve optimum life with carbonate

cathode material on nickel base metal (with BaO reducing agents incorporated in the base metal). With the advent of the barium aluminate dispenser cathodes in 1955, current densities of 2 A/cm^2 at 1000°C were achieved with up to 10 A/cm^2 at 1200°C . These cathodes were made by impregnating a porous tungsten plug with barium aluminate powder. The barium necessary for activation is generated by reaction with tungsten.

Under industrial sponsorship, experiments on cathode life vs current density have recently been initiated at Los Alamos. Test diodes have been fabricated and tested using the TIC standard tungsten thin-film base, regular (Ba, Sr, Ca) carbonate-photoresist as cathode material, and a 5- x 5-mil cathode area. Emission levels of 10 A/cm^2 or greater at 800°C have routinely been observed (Fig. VI-1). The anode consists of titanium sheet mounted 5 mils above the cathode. Figure VI-2 shows a test pattern used to test four diodes simultaneously. Figure VI-3 shows the same structure with one anode welded in position on the sapphire substrate. The titanium sheet has folded up "wings" to provide additional thermal dissipation in the anode.

It is believed that the carbon in the photoresist acts as a reducing agent for these cathodes. The following reactions may occur:

A more efficient reaction may take place in the TIC cathode because the carbon is available in the mixture; whereas in the standard receiving tube cathodes, reducing agents were diffused from the base metal (nickel), and thus, barium conversion was limited by the rate of diffusion at a specific temperature.

High current life tests using this structure will be started in the near future. (Previous life tests on TIC devices were conducted at approximately 200 mA/cm^2 .) Also, no attempt has been made to date to fabricate a triode for operation at these levels. Future planning includes work on both these items using the four-device structure shown in Fig. IV-1 to evaluate the cathode lifetime as a function of current density for a given temperature. Multiple tests will be performed to determine the effect of temperature.

C. Conclusions

The TIC devices are routinely producing current densities approaching 20 A/cm^2 at 800°C as compared with the older figures of merit of 100 mA/cm^2 in conventional oxide-coated vacuum tube cathodes. This could have a large impact

Fig. VI-1. Diode characteristics at 800°C.

Fig. VI-2. Cathode substrate.

Fig. VI-3. Substrate with one anode welded in position above the cathode.

on both functionality and speed of TIC circuits if long lifetime can also be demonstrated under these conditions.

D. Recommendations

1. At a very minimum, life vs current density and life vs substrate temperature experiments should be continued for existing cathode techniques.
2. Advanced, more durable cathodes as described above should be explored as part of any long-term TIC program.

VII. POWER DEVICES

A. Background

The TICs could be of interest as triode power switches or power diodes for many systems such as the space reactor because of their high tolerance to total radiation dose. This preliminary evaluation addresses this application as requested at a meeting between Los Alamos personnel and an SP-100 contractor initiated at the request of the contractor.

It must be mentioned at the outset that the TICs have been developed as small signal linear or low power digital devices, not as high current or power devices. Therefore, a complete evaluation for power applications would require a substantial effort in power device design as well as power device fabrication and evaluation in order to verify performance. In addition, package design is an important consideration. Because the device must be packaged to withstand shock and vibration and because the devices operate at 700-900°C, thermal radiation characteristics and thermal capabilities of the package are important. Further, lifetime data vs current density and operating temperature are not available at this time, although preliminary tests are currently under way as described in Section VI.

B. Analysis of Two Configurations

Two possibilities are considered for handling 2-kW increments from the source (power and operating voltage was supplied by the SP-100 contractor). The first is as a conventional switch where most of the 2 kW would be dissipated in a load resistor. In the second possibility, the entire 2 kW would be dissipated in a metal anode, which is part of the device. That is, the device

would be connected directly across the source and there would be no load resistor. The device would be designed so that in the on state the device current would be $2000/(\text{source voltage})$.

The first design using the conventional low-power switch shows some promise even for a source voltage as low as 100 V. However, it should be noted that, because the total cathode area is proportional to the total current, device size is reduced and device design is simplified as the source voltage is increased and device current is decreased. Therefore, higher source voltages are more favorable to the devices.

The evaluation of the low-power switch is based on the worst case of 100-V source and 20-A switch current. As indicated below, there are insufficient data to justify detailed calculations or evaluation of other source voltages, although as described later, higher voltage operation at lower current simplifies device design.

As a starting point, a current density of 1 A/cm^2 would require 20 cm^2 of active cathode area, and an "on" voltage of 5 V would require that the device be capable of dissipating 100 W. Although a triode is being evaluated, the diode current density equation can be used to calculate the approximate anode-to-cathode spacing:

$$J = 2.335 \times 10^{-6} V^{3/2}/S^2, \quad (\text{VII-1})$$

where S is the anode to cathode spacing in centimeters.

Using the above conditions, the required spacing is $5.1 \times 10^{-3} \text{ cm}$ or 2 mils. Since substrate-to-substrate spacings of 2 mils cannot be maintained with the vertical triode structure (grid and cathode on one substrate and anode above on another substrate), the vertical triode probably cannot be used. However, the planar triode (cathode, grid, and anode on the same substrate) would allow an anode-to-cathode spacing of 2 mils.

Equation (VII-1) was derived for a vertical structure and should only be used as an approximation for a planar device. However, assume that a current density of 1 A/cm^2 can be obtained from a multiple device planar triode with a cathode-to-anode spacing (center-to-center) of 2 mils. Figure VII-1 shows a single device of this type. It must be emphasized that there is very little data on planar devices of this geometry and that the following calculations require experimental verification.

Fig. VII-1. Space power reactor planar triode dimensions.

From Fig. VII-1, the total device area is four times the cathode area or 80 cm^2 . Four 2.2-in.-diam substrates would supply this device area with 200 mils around the outer edge of each substrate for bonding and mounting.

The total power radiated from a pair of 0.75-in.-diam by 0.03-in.-thick substrates operating at 800°C can be reduced to below 10 W by the methods used in Section IV. The ratio of the edge area to total substrate area is

$$A_e/A_t = 4t/(d + 4t) \quad , \quad (\text{VII-2})$$

where t is the substrate thickness and d is the substrate diameter. For $d = 0.75 \text{ in.}$ and $t = 0.03 \text{ in.}$, $A_e/A_t = 0.14$. Then for a total power of 10 W, the power radiated from the two substrate edges is approximately 1.4 W, and the power radiated from the two substrate surfaces is approximately 8.6 W or 1.5 W/cm^2 . These data are used to calculate the heater power required because heater power has not been measured for 2.2-in substrates or for a stack of more than two substrates.

For a stack of four 2.2-in substrates, the surface power radiated from the two end substrates would be 74 W. The ratio of the total edge area to the two end surfaces for 30-mil-thick substrates is 0.11. The power radiated from the four edges is $P_e = 8.1 \text{ W}$, and the total power radiated is $P_t = 82 \text{ W}$. Thus, an estimate of the heater power required to maintain the four substrates at 800°C is 82 W. This can be reduced by additional shielding or by reducing the standby temperature. For example, a standby temperature of 700°C would reduce the estimated heater power to 55 W.

The voltage gain of the device in Fig. VII-1 is estimated to be about 4. The device would be turned on with about +2 V and turned off with -25 V. The input power is determined primarily by the grid-to-cathode leakage resistance, which is quite high. It is estimated that the power gain would be >1000 .

These values are based on preliminary calculations of planar device characteristics. At Los Alamos, only a few planar devices have been characterized and no power devices have been characterized. One small signal device that has been characterized has geometry similar to that of the device in Fig. VII-1 but with substantially different electrode dimensions. Its characteristics were voltage gain = 4 and current density = 100 mA/cm^2 at 5 V and 300 mA/cm^2 at 10 V. These current densities would be increased if the anode-to-cathode spacings were reduced to 2 mils.

A second possible device for this application would dissipate the entire 2 kW in the anode. Preliminary calculations indicate that this concept has possibilities for source voltages above 200 V. For example, with a source voltage of 400 V, the device would be designed so that in the "on" state the device current would be 5 A at 400 V anode to cathode. The metal anode would have to be designed to radiate 2 kW; this could be done at relatively high temperatures (perhaps $>1000^{\circ}\text{C}$). Before further work is done on this concept, it must be determined if it offers any system advantages or would even be compatible with the system.

For example, consider switching 5 A from a 400-V source. If a vertical triode with a 100-mil anode-to-cathode spacing is used, the current density calculated from Eq. (VII-1) is 289 mA/cm^2 . Current vertical devices have a device-to-cathode area ratio of 2:1 and a voltage gain of about 50 with 100-mil anode-to-cathode spacing. Thus, a cathode area of 17 cm^2 and a device area of 34 cm^2 are required. The device would consist of a 2-in substrate on each end of a common anode. The size and shape of the anode could be adjusted to accommodate the required radiated thermal power.

C. Conclusions

Because of the small cathode-to-anode distances achievable in the planar device form of TIC technology, power devices with high stand-off and low forward drop in the on state (as compared with conventional vacuum devices) may be possible. Also, power devices may have important properties for space reactors in their ability to withstand total dose environments and may be useful adjuncts to TICs with applications mentioned in Section VIII.

D. Recommendations

1. Power devices should be designed and tested in order to augment the capabilities of TICs in controlling power.
2. Current density vs life tests must be conducted in order to properly evaluate the technology for possible high-power applications.

VIII. APPLICATIONS

A. Approach

Since the general rationale for this project is to evaluate applicability of TIC technology to weapons systems and concurrently to develop insights for guiding future TIC development programs, broad discussions with both governmental agencies and industry (Ref. Section VIII.B) have been initiated. Based on those discussions, varying emphasis has been given to the types and depth of the technical evaluations performed. Additionally, based on sponsor guidance suggesting the importance of applications, a small amount of funding from the program (\$30k) has been set aside for a contract to one of several companies to perform an independent evaluation of the TIC technology vs applications. After the competitive RFP process, R & D Associates (RDA) has been selected to carry out this analysis. Also, since beam weapons represent an important possible threat in the future, Dr. George Messenger has been retained by Los Alamos as a consultant to evaluate and report upon the threat posed to electronics by beam weapons and to evaluate the TIC technology as related to that emerging weapons concept.

The first phase of understanding potential TIC applications was to initiate a broad-based set of discussions with both industry and military personnel. Because TICs represent a new concept to most of the military weapons systems community, it was expected that these discussions would initiate dialog that would, in general terms, define possible applications and/or technological issues that should be further addressed in this program. More detailed assessments would be left to RDA and Dr. Messenger.

B. Discussions/Presentations/Meetings

For brevity, the discussions, presentations, and meetings to date are listed in Tables VIII-1 and VIII-2. Table VIII-3 is an additional list of requests for data from industry (visits to several of these organizations have been promised in the next few months).

TABLE VIII-1

MEETINGS

<u>General Meetings</u>	<u>Sponsor</u>	<u>Presenter</u>	<u>Location</u>
Space-Based Space Surveillance Technology Briefing to Industry	AF Space Technology Center	J. B. McCormick	Air Force Weapons Laboratory
Hardened Electronics and Radiation Technology Conference	DNA/Oak Ridge	G. Messenger ^a	Oak Ridge
Solid-State Vacuum Tube Technology Seminar	JPL ^b	J. B. McCormick	JPL
Neutral Beam Technical Interchange Meeting	AF Space Technology Center	J. B. McCormick ^c G. Messenger ^c	Air Force Weapons Laboratory

^aOutstanding paper award; subject: Susceptibility of Exo-Atmospheric Electronic Systems to Neutral Beam Weapons.

^bThis meeting was an effort by JPL/Los Alamos to bring together others interested in vacuum tube technology to begin sharing data/objectives.

^cTwo papers: "Thermionic Integrated Circuits for Hardening Electronic Systems," coauthored by B. McCormick and G. Messenger, and "Pulsed Neutral Beams to Enhance Dose Rate Failure Mechanisms" by G. Messenger.

TABLE VIII-2
APPLICATIONS DISCUSSIONS

<u>Name</u>	<u>Organization</u>	<u>Location</u> (T = There) (LA = Los Alamos)
Prof. Pat Parker	Navy Postgraduate School	T
Admiral Bob Monroe	Los Alamos consultant	LA
Brig. Gen. James L. Crouch	Data Systems HQ/SAC	LA
Al Devitt	" " "	LA
Lt. Col. James Hayes	" " "	LA
Dr. Richard L. Wagner	Assistant to the Secretary of Defense (Atomic Energy)	LA
Capt. Jim Patton	Naval Ocean Systems Center	T
Jim Ramsey	" " " "	LA
Maj. Ron Lord	BMO, Norton AFB	T
Vincent Hungerford	Naval Ordnance Station	LA, T
Bill Yeckley	" " "	LA, T
Dick Montgomery	JPL-Army Advisory Group	T
Robert D. Castater	Chief of Science & Research, HQ/SAC	T, LA
Francis O'Mera	Chief, Operations Analysis, HQ/SAC	LA
James Vinarski	Operations Analysis, HQ/SAC	LA
Dr. Theodore M. Hardebeck	Operation Analysis, HQ/SAC	LA
Gene Schroeder	Applied Research, HQ/SAC	T, LA
Henry Gray	Naval Research Laboratory	T
Mike Gauthier	JPL-Rad Hardness Group, SP-100 Program	LA, T
Jim Graf	JPL, SP-100 Program	T
Nick Yaru	Sr. Vice President, Hughes Aircraft	T
Dick Richmond	Hughes Aircraft - Combat Information, Surveillance and Sensor Systems	T
Jim Raymond	Mission Research Corporation	T
Dr. Larry Gray	Naval Ocean Systems Center	T
Mike Gordon	Martin Marietta	LA
Rao Yadavalli	" "	LA
Dale Vaslow	GA Technologies	T
Al Lieber	" "	T
Comdr. Al Hughes	Navy	T
Capt. Blockinger	DNA	T
Walt Ware	Mission Research Corporation	T
Phil Jessen	" " "	T
Khosrow Bahrami	JPL, Space Reactor Program	LA, T
Mr. Bob Kupperman	Los Alamos consultant	LA, T
Dr. Howard Phillips	Aerospace Corporation	T
Dr. Frank Rose	Naval Surface Weapons Center	LA
Capt. Bud Powers	Navy, PM-23	T
Lt. Col. Brown	DNA, Albuquerque	LA

<u>Name</u>	<u>Organization</u>	<u>Location</u> (T = There) (LA = Los Alamos)
Maj. Rolfes	" "	LA
Larry Darda	Hughes Aircraft, Space & Communications	T
Tom Bristol	Hughes Aircraft, Ground Systems Div.	T
Ken Downing	Hughes Aircraft	T
Bob Hengstebach	" "	T
Leroy Lakin	" "	T
Al Lepis	" "	T
H. T. Peterson	" "	T
Bob Reeves	" "	T
Bill Sagey	" "	T
Joe Santana	" "	T
Wayne Schenet	" "	T
John Singleton	" "	T
Maj. Swenson	AF Space Technology Center	T
Dan Payton	AF Weapons Laboratory	T
Representative	a jet engine manufacturer ^a	LA
Maj. Mike Starch	HQ/SAC/XPQM	T
Maj. Lou Mills	" "	T
Capt. Bruce Thleman	" "	T
Maj. Steve Parker	" "	T
Thomas Jorgensen	" DEXT	T
Warren Lee	" NRA	T
Capt. Leo Florence	" XPXS	T
Roger David	" XPXF	T
Joe Mulcahy	" XOBM	T
Ray Tang	Hughes Aircraft	T
Steve Warfield	" "	T
Bill Wright	" "	T
Maj. Joel Benson	HQ/DNA	LA
Maj. Nathan Mathewson	Academy of Health Science, US Army	LA
Col. Joe Jarboe	AF Systems Command	LA
Col. Rod Bartholemew	" " "	LA
Col. Tom Hohman	" " "	LA
Col. Jerry Mason	" " "	LA
Col. John Bates	" " "	LA
Col. Mike Burke	" " "	LA
Col. Dave Carlson	" " "	LA
John Bayless	TRW	T
Dr. Signori	Defense Communications Agency	T

^aName deleted because proprietary contract with Los Alamos is being negotiated to evaluate jet engine requirements.

TABLE VIII-3
REQUESTS FOR DATA

<u>Name</u>	<u>Organization</u>
Carl Casiky	RCA ^a
Joe Veltri	Sperry Research ^a
Vince Teofilo	Lockheed
Truman Nybakken	Delco Systems ^a
Bill Flemming	TRW ^a
D. L. Beeqley	Lockheed

^aVisits/discussions have been requested and will be initiated as time permits.

C. Conclusions

As can be seen from the preceding section, there have been a substantial number of discussions regarding the TICs. Because the TICs are in a developmental stage, many of the discussions were followed with "what if" questions on both sides. From these discussions some general trends are emerging.

First, word of the technology is spreading rapidly, and as a result, people are contacting Los Alamos for information and briefings. Because military systems and their operational envelopes are designed with existing/verified hardware, personnel/organizations most curious about the TICs are generally those who are working on future systems. The ability of the TICs to survive and possibly operate through a wide range of radiation and high-temperature environments is stimulating those people to broaden their concept of possible missions and capabilities of future systems. New threats such as beam weapons, lasers, and enhanced effects weaponry as well as new strategies such as flexible response during nuclear conflict, air land 2000, and nuclear-reactor-powered satellites present the possibilities for environments through which conventional electronics will have difficulty surviving and for which the penalty for electronic failure is large.

The concept of utilizing the TICs in conjunction with shielded semiconductors has been universally supported as the appropriate approach for employment of the TICs. As a result, TICs with small- to medium-scale level of integration have been projected to be extremely useful; projected heater powers of a couple of milliwatts per device are acceptable; and speeds and bandwidths projected suggest a diversity of applications. Concern for EMP is large. High-temperature operation is appealing for a number of applications, and power devices using TIC technology would complement TICs in providing a full systems capability.

As described early in this report, a number of applications have been thought to show promise. A few are listed below.

- o Launch control for hard mobile missile - BMO, Norton AFB
- o Selective hardening of satellites - Hughes Aircraft, Air Force Systems Command
- o Hardened RPVs and battlefield sensors - AF Systems Command, Hughes Aircraft, Mission Research Corporation
- o Reactor safety, military, and nonmilitary - GA Technologies, Inc.
- o Arming, fuzing, and terminal guidance - Sandia National Laboratories, Naval Weapons Systems Center
- o Hardened controls/power devices for both space and terrestrial reactors - JPL, GA Technologies, Inc., Lockheed, Martin Marietta, GE
- o Hardened C³I - Defense Communications Agency, Strategic Air Command, JPL
- o Jet engine instrumentation/control ("fly by wire") - Strategic Air Command, a jet engine manufacturer*

Two recurring themes in the discussions to date are

- o Timeliness of the availability of TIC devices (How soon?)
- o Concern for validation (How can delay from R&D to fielding be minimized?)

Both of these are important issues in structuring a TIC program and are reflected in the recommendations of Section I.E.

*Name deleted because proprietary contract with Los Alamos is being negotiated to evaluate jet engine requirements.

D. Recommendations

There is little doubt after the discussions held to date that if the TICs fulfill current technical expectations they will find applications in a number of military systems. Therefore, an aggressive TIC development program is recommended even before completion of detailed analyses by RDA and Dr. Messenger. In general, this conclusion not only derives from the interest exhibited to date but also because of the breadth of applications discussed, which are within the capabilities of a projected generic TIC technology. It must be emphasized, however, that this program not only should be a technological program but should include funding for continued applications evaluations and discussions with industrial and governmental personnel responsible for planning and developing future generations of military hardware. In this manner, as the technical performance is verified, the way can be paved for an orderly transition of this technology from the lab to the field.

IX. REFERENCES

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2. R. W. Klaffky, "Radiation-Induced Conductivity of Al_2O_3 ," in "Special Purpose Materials," US Department of Energy Annual Progress Report, October 1, 1979, DOE/ER-0048/1 (April 1980).
3. P. P. Coppola and R. C. Hughes, "A New Pressed Dispenser Cathode," Proc. of the IRE (March 1956), pp. 351-359.
4. J. E. Beggs, "Characteristics of Electron Tubes Having Clean Electrodes," IRE Transactions of Electron Devices (April 1958), p. 56.
5. Karl Spangenberg, Vacuum Tubes (McGraw Hill, New York, 1948), pp. 185-186.
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APPENDIX

TIC Speed/Bandwidth Test Structures and Plans

Two test patterns need to be fabricated for measurement of the GBP and for verification of predictions. One would be a spiral single-stripe cathode device and the other would be an interdigitated device. Both would have the same cathode area for a given cathode width. Measurements should first be made on a dummy substrate with a heater, but no device pattern, mounted in a header. A substrate with both heater and device can then be measured. All measurements would be made both hot and cold. For ease of mask making, the test devices will be rectangular as shown in Fig. A-1. To minimize the effects of pin capacitance, wherever possible a blank pin would be left between pins used for connections. If adjacent pins must be used, then device electrodes already having high capacitance would be connected to adjacent pins. Figure A-2 shows possible pin choices.

For the spiral single-stripe cathode, as large a cathode area as possible must be obtained while maintaining the same line widths and spacings as would be used in an actual small-geometry, single-stripe device. The spiral would be in the form of a square 384 mils on a side (Fig. A-3). For a 1.5-mil-wide cathode, the length of the cathode is 2550 mils and the cathode area is 3825 sq mils. The first leg and corner of the spiral are shown in Fig. A-4(a). The dimensions of the lines and spacings to be used in this example are: grid (G) width, 1 mil; cathode (K) width, 1.5 mils; grid-to-cathode (G-K) spacing, 0.25 mils; cathode shield (KS) width, 36 mils; cathode shield-to-grid (KS-G) spacing, 4 mils; anode (A) width, 4 mils; anode-to-shield (AS) spacing, 36 mils; and anode shield-to-anode (AS-A) spacing, 4 mils. The first leg and corner of the anode are shown in Fig. A-4(b).

If an interdigitated structure of 29 cathode stripes (each 1.5 x 88 mils) is used, the cathode area is 3823 sq mils. Figure A-5(a) shows this configuration using 1-mil grid stripes and 1-mil spaces between the ends of grids and cathodes. The anode substrate is shown in Fig. A-5(b).

The following test procedure would then be implemented. Dummy substrates with heaters for both anode and cathode would be made and mounted on headers sealed in envelopes. Substrates would not have device patterns but

would include all bonding pads and interconnection metal up to the device terminals. Several headers would then be measured to see if they have the same pin capacitance. Both hot and cold capacitance measurements would be made. Next, substrates having heaters and device patterns would be mounted on headers and sealed in envelopes. Both hot and cold capacitance measurements would again be made. On the hot measurements, the cathode may have to be biased so it is cut off. On all measurements, a guard voltage would be applied to all but the two terminals being measured and to the ring. Finally, transconductance measurements would be made.

If $[Y_{iT}]$ is the indefinite admittance matrix for the total configuration of the header, wiring, and substrates with the device; $[Y_{iD}]$ is the indefinite admittance matrix for the header, wiring, and dummy substrates; and $[Y_{ii}]$ is the indefinite admittance matrix for the intrinsic device, then

$$[Y_{iT}] = [Y_{iD}] + [Y_{ii}] \quad (A-1)$$

or

$$[Y_{ii}] = [Y_{iT}] - [Y_{iD}] \quad (A-2)$$

Once $[Y_{ii}]$ is known, the device is completely characterized for small-signal operation, no matter what terminal connections are used. It should be noted that even for small-signal operation, the device has six effective terminals: anode, anode shield, cathode, cathode shield, grid, and heater. (For small-signal operation, both heater terminals are assumed to be electrically the same.) The process can then be repeated for a variety of expected geometries.

Fig. A-1. Substrate layout of GBP test device.

Fig. A-2. Pin choices for GBP test device.

Fig. A-3. Cathode length, spiral GPB test device.

(a)

(b)

Fig. A-4. Example of spacing for single-stripe cathode.
(a) Grid-cathode structure. (b) Anode structure.

(a)

(b)

Fig. A-5. Structure of interdigitated GBP test device.
(a) Grid-cathode shield. (b) Anode shield.