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APPROACHES TO HIGH TEMPERATURE ELECTRONICS

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MASTER

APPROACHES TO HIGH TEMPERATURE ELECTRONICS*

INTRODUCTION

After preliminary investigation, three potentially viable approaches to the problem of constructing high temperature electronic systems (operable to 500°C) have emerged. The three approaches utilize: 1) miniaturized vacuum electronics, 2) III-V compound semiconductors, and 3) silicon carbide films.

In this paragraph, the major aspects of the development programs for the three different approaches are briefly examined; additional discussion appears in the body of this note.

- (1) Although there are difficulties in fabricating the small structures and uncertainties about the use of the field emitter point cathodes, the vacuum tube approach utilizes an extensively studied technology. It has a high probability of yielding useful devices.
- (2) The use of III-V semiconductors involves established materials but raises some developmental questions concerning the technology of device fabrication. It does, however, have the usual density and power advantages of an integrated electronics system.
- (3) Using silicon carbide films would require work on the material itself in addition to the problems of device fabrication. These films offer the potential of great durability in addition to the advantages of solid state devices.

VACUUM ELECTRONICS

An assembly of miniaturized vacuum tubes appears to offer the necessary resistance to the hostile environment. While this approach sacrifices a degree of microminiaturization, extreme miniaturization is not required in many high temperature applications. Figure 1 shows a small segment (only four tubes) of a ceramic sandwich in which an array of vacuum triodes would be mounted. The design goal would place about 60 triodes per square inch. An initial guess is that typical ceramic sandwich would be six square inches and would hold 360 vacuum tubes.

*Work performed under the auspices of the U.S. Atomic Energy Commission.

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The principal reliability questions would seem to relate to the mechanical properties of the ceramic-metal seals and the integrity of the vacuum. Because typical tubes experience temperatures in excess of 500°C during manufacture, the difficulties suggested by this question probably can be overcome. It would simplify the construction if a cold cathode could be used; field emitting point structures are proposed for this purpose. The adoption of a cold cathode and the small size of these tubes raise some questions about the electrical behavior. Predictions of the electrical characteristics will have to be generated. There is reason for optimism because many high temperature instrumentation and control problems are unlikely to require extremely high performance electronics.

A possible technology for interconnecting the tubes of a ceramic sandwich into a logic network, linear amplifier, or other active electronic circuit, would involve the deposition of a thick film passive network on the surface of the ceramic, and the attachment of the resistors and capacitors, as one would for hybrid circuitry. Because one would have several hundred triodes in a single ceramic structure, the construction of circuits of considerable complexity would be possible on one such structure.

SOLID STATE APPROACHES

Existing, solid state, active devices require the formation of selected p-type and n-type regions. The nature of the charge carrier introduced by the impurities in the semiconductor lattice determines the type, p or n, of a region. This distinction disappears when the concentration of electron-hole pairs produced by purely thermal processes exceeds the impurity concentration. As a rule of thumb, the upper limit on the concentration of thermal pairs, $n_i(T)$, must be two orders of magnitude lower than the impurity concentrations. Since the key factors in fixing, $n_i(T)$, are bandgap energy and temperature, T , it is essential to select a large bandgap material. This eliminates germanium and silicon and suggests, among others, the III-V, compound semiconductors or silicon-carbide.

Figure 1

GALLIUM PHOSPHIDE - A SOLID STATE APPROACH

Among the possible III-V compounds, one attractive material is gallium phosphide, GaP. The calculated intrinsic carrier concentration in GaP is plotted as a function of temperature in the following table.

Temperature °C	Intrinsic Carrier Concentration, (Cm^{-3})	
500	0.8×10^{14}	to 0.8×10^{15}
600	0.8×10^{15}	to 0.8×10^{16}
700	0.5×10^{16}	to 0.5×10^{17}
800	0.21×10^{17}	to 0.21×10^{18}

The uncertainty in n_i arises from uncertainties in the density of states effective mass values. Assuming that impurity concentrations of $10^{19}/\text{Cm}^3$ can be achieved and allowing 100°C for the temperature rise of the junctions, operation at ambient temperatures exceeding 600°C appears to be possible. The bandgap is indirect and moderate lifetimes of minority carriers are possible.

Discrete devices for high temperature operation have been fabricated in GaP including SCR's which operated in a 500°C ambient. The SCR's did show some increase in leakage current at this temperature. Field effect devices have also been reported.

Good quality GaP wafers are available at about \$50/inch². The problems, reported several years ago, of irregular doping due to crystal imperfections, and of phosphorous out-diffusion at high temperatures are no longer incurred due to improved technology.

As a first guess, a typical n-channel MIS device with polycrystalline silicon interconnects would be possible in an LSI configuration.

SILICON CARBIDE FILMS - A SOLID STATE APPROACH

Silicon carbide has long been under consideration as a high temperature electronic semiconductor but it has been difficult to fabricate adequately large single crystals. It may be possible to form satisfactory β phase SiC (SiC occurs in several different crystal structures)

by converting thin films of single crystal silicon, on a sapphire substrate to silicon carbide. There are two approaches, each of which has demonstrated at least some degree of success. Ion implantation followed by annealing has been shown to produce islands of β -SiC near the surface of silicon crystal. Conversion has also been achieved by heating silicon in a carbon rich (argon-methane) atmosphere. This second approach requires a considerably higher temperature (1300°C) than the implantation method (1000°C).

By choosing to form the SiC as a thin film on an insulating substrate one achieves several advantages. First, the supply of silicon is limited, unlike the situation in which bulk crystals are ion implanted. Hence, one is not in the situation of excess silicon which leads to the formation of SiC islands in a Si matrix. Second, all but selected areas of SiC, about 100 microns on a side, are removed to form the final active electronics. Hence, the regions of single crystal material need only be of a size $100\mu\text{m} \times 100\mu\text{m} \times 1\mu\text{m}$. By passing the SiC on the sapphire substrate thru a furnace with a temperature gradient one may be able to anneal these small volumes of SiC into single crystals. This seems far easier than the problem of forming a large single crystal of SiC that functions both as substrate and electronics.

Following a procedure similar to that used on GaP, one can compute the intrinsic carrier concentration in β -SiC. Within the limits of the accuracy of this type of calculation, there is very little difference between β -SiC and GaP. Again the bandgap is indirect. The technology of making devices of SiC parallels the conventional silicon technology with the exception of the necessity of depositing masking films. It is anticipated that the resulting structures would be similar to the P-channel MOS circuits currently being fabricated from silicon-on-sapphire wafers.

Temperature (°C)	Intrinsic Carrier Concentration (Cm^{-3})
500	0.9×10^{14}
600	0.96×10^{15}
700	0.65×10^{16}
800	0.31×10^{17}
900	0.11×10^{18}

ANTICIPATED PROGRAMS

The organization of effort on the problem of producing a high temperature electronic system is necessarily dependence on the nature of the users goals. If a high probability of success on a relatively short time scale is desired, then emphasis on vacuum tubes appears to be reasonable. If a more sophisticated, higher density system, is desired, if greater risk and a moderately extended time scale can be tolerated, then the solid state approaches appear to be the more rewarding.

In absence of any such specific constraints the following program should be considered. A minimal series of preliminary experiments aimed at assessing the promise of each of the above approaches would be conducted. Those approaches which exhibit problems whose solutions require an effort not possible within the scope of the program would be dropped from consideration. In a succession of increasingly detailed evaluations, the approach of greatest over-all merit would be selected. Using this approach a prototype electronic package would be constructed.

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