HIGH-TEMPERATURE ELECTRONICS--AN OVERVIEW

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Introduction

The purpose of this paper is to provide an overview of contemporary high-temperature electronics. To that end, it contains brief remarks on its history, an enumeration of the groups or individuals known to us who are now active in the field with their interests and objectives, a discussion of the current state of the art, and an attempt to identify the major areas where new developments are needed for the future.

History

The development of electronic technologies for high temperatures began in the late 1950s and early 1960s (1,2,3) with anticipated needs for the Space Program. While progress was made, notably in the development of high-temperature (400°C) commercially available vacuum tubes, the rapid development of thermal control technology for spacecraft obviated the need for this electronics, so the development effort subsided. The advent of a national energy program, specifically the Geothermal Energy Program, precipitated anew a concerted effort to develop high-temperature electronics. This effort started in early 1976. Since then, further stimulus has come from needs for high-temperature oil and gas well logging and jet engine monitors.

Active Groups in HT Electronics R&D

The groups who are actively pursuing the development of high-temperature electronics include but are probably not limited to the following. Prime movers are the government sponsors, DOE/The Division of Geothermal Energy (with some small support from fossil fuel groups), and the Navy/NAVAIR with NRL as program manager. Their prime contractors are Sandia Laboratories for DOE and General Electric-Evendale cooperating with General Electric, Schenectady, for the Navy. Sandia, in turn, has a

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number of contracts for study, development, and commercialization in specific areas. These are with Teledyne-Philbrick for hybrid manufacture; Harris Semiconductor Corporation for IC development; Texas A&M University for magnetics and gallium arsenide studies; the University of Arizona for thin film capacitor and integrated thermionic circuits passive devices development, MOS modeling and sensors development; Purdue University for thick film studies; Clemson University for IC evaluation and studies; and McDonnell-Douglas for gallium arsenide device development. Sandia purchases which have prompted successful development efforts have been placed with General Magnetics for transformers and magnetic multipliers, and with Cermalloy for thick film inks.

Los Alamos Scientific Laboratory with DOE/DGE funding has for several years been developing an integrated thermionic circuit (ITC) technology (4). The objective is to provide thermionic circuits in which several "tubes" and ancillary passive components are enclosed in a single vacuum package in a miniature, dense format. A circuit would then function, for example, as an operational amplifier or logic gate. Tube elements, resistors, and capacitors are thin films deposited and defined on refractory substrates using standard techniques.

Oak Ridge National Laboratory with DOE funding has been conducting a program to develop circuits for operation in the sodium coolant loop of the Clinch River Fast Breeder Reactor core during its startup phase. Their requirements are for a pulse amplifier and a dc-to-dc converter (6 volts to 20 volts) operating at 230-250°C. The circuits take voltage signals from a self-powered neutron counter and convert them through an appropriate piezoelectric transducer to ultrasonic signals in the sodium loop which are detected outside the reactor core. The circuits will be battery or radioactive source powered so that no wires to the outside are required.

An investigation of the important area of packaging technology of integrated circuits recently has been undertaken by RCA, Moorestown, New Jersey.

Significant and growing factors in the high-temperature electronics field are the logging companies and electronics firms who supply them. A number of these companies are conducting development programs in this technology, the former for their in-house use and the latter for sale. It is our impression that most of this work has the 200°C temperature regime as its present target since this will satisfy most oil and gas well logging and a great deal of geothermal logging as well.

State of The Art

The current state of the art in high-temperature electronics can be expressed in a number of ways. One which provides a very broad brush view is to consider the various temperature regimes which each development effort serves (Fig. 1) and the state of "maturity" of the development. According to this view, the state of the art is about as follows (Fig. 2):

RT to 175-225°C (for high-temperature oil and gas well logging). Little special development has been needed for this temperature regime. Activity has been devoted to identifying those devices, components, and techniques developed and marketed for standard (125°C maximum) use which survive and operate at the higher temperature. The first commercial data sheets for 200°C qualified MSIs are just now becoming available. Likewise, several hybrid manufacturers have advertised and are apparently delivering circuits for these temperatures.

RT to 275-300°C (for geothermal logging jet engine and nuclear reactor monitoring). This regime has been the major focus of Sandia's program to date. A hybrid technology is now at the edge of commercial availability. Development of MSIs (OP-amps, gates) is just beginning, and commercialization may be 2 to 3 years away. LSI development is likewise just beginning and is therefore a number of years from commercialization.

RT to 350-450°C (for geothermal logging and nuclear reactor monitors). Developments for this regime focus on a substantially upgraded hybrid technology, magnetics, and III-V compound semiconductors. For the most part, this work is just beginning.

500°C and higher (for geothermal and magma exploration). The prime technology for this regime is the thermionic integrated circuit which is under development. Circuits of this type have been operated in the laboratory although there are a number of significant technical problems yet to overcome, including development of low-leakage capacitors. Magnetic amplifiers, multipliers and similar devices may also be applicable for some measurements.

Future Directions

There are many technical problems remaining for high-temperature electronics, and although no attempt will be made to enumerate all of them, some broad categories are clear.

Capacitors. A significantly broader range of capacitors is needed including, for temperatures up to 300°C, hybrid compatible and high-voltage capacitors with values from 0.01 to 1.0 μ F, capacitors for monolithic silicon circuits and energy storage capacitors; for temperatures greater than 300°C all values above 1.0 nF and all voltages. For the highest temperatures the problem of leakage through the dielectric due to thermally activated conduction will present a fundamental and difficult problem.

Diodes. The basic problem with diodes at high temperatures is leakage. This limits the use of Si diodes at 275°C. Therefore devices fabricated from wider band gap materials, probably III-V compound semiconductors, need development.

Si MOSFETs. Current commercial Si MOS transistors have not proven to be stable at 275°C. Design and production modifications, increased substrate doping levels, and improved gate oxide cleanliness, have yielded satisfactory devices. Developing commercial sources of these remains to be accomplished.

Si ICs. We know of no integrated circuits which operate satisfactorily and for long times (e.g., 100 hrs.) at 275°C although commercial devices are just now becoming available for about 200°C. An operational amplifier is under development for the higher temperature. A much wider array of MSI circuits is needed. LSIs, microprocessors and memories, are just starting development for 275°C use, but this will be a major undertaking.

III-V Transistors and ICs. GaAs MESFETs which have been tested at 275°C have proven to be unstable. The development of discrete transistors using GaAs or other III-V compounds and alloys for 350°C and higher temperatures is in its very early stages, with metallization and passivation studies in progress. III-V compound ICs for high temperatures appear to be a distant prospect.

ITCs. Integrated thermionic circuits, which are one of the few prospects for use at 500°C and above, are well along in development although difficult problems remain (capacitors, packaging). Applications at these high temperatures may be a number of years away, however.

Magnetics, Batteries, Transducers. Good progress has been made in the magnetics area with low-voltage, commercial transformers available for use to 500°C. Basic studies of magnetic materials are in progress. In the transducer area, a low sensitivity bourdon pressure gage for 275°C has been tested and a very high resolution quartz gage for that temperature is being developed. For other measurements and higher temperatures, a significantly broader effort will be required. Batteries, for long-time operation over the wide temperature ranges of interest, are not available and probably represent a major technical challenge. High-temperature batteries for short-time operation (thermal batteries) are available.

References

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TEMPERATURE REGIMES
FOR
HIGH TEMPERATURE ELECTRONICS

<u>TEMPERATURE RANGE</u>	<u>APPLICATIONS</u>	<u>COMMENTS</u>
125°C	STANDARD MILITARY SPEC.	
0 TO 175-225°C	HOT OIL & GAS WELL LOGGING, LOW TEMP GEOTHERMAL	USES SELECTED 125°C ELECTRONICS
0 TO 275-300°C	GEOTHERMAL, JET ENGINE MONITORING	UPPER TEMPERATURE LIMIT OF CONVENTIONAL SI DEVICES
0 TO 350-450°C	GEOTHERMAL	III-V COMPOUND TRANSISTORS
500 AND HIGHER	MAGMA AND NEAR MAGMA EXPLORATION	INTEGRATED THERMIONIC DEVICES, MAGNETICS

HIGH TEMPERATURE ELECTRONICS STATE OF THE ART

(11/79)

TECHNOLOGY PROBLEMS FOR THE FUTURE (11-7-79)

COMMERCIAL AVAILABILITY	275-300°C	350-500°C	>500°C
0-2 YRS	BRICK CAPACITORS STORAGE CAPACITORS SI MSI (OP-AMP)* MOS SI TRANSISTORS*	CAPACITORS RESISTORS MAGNETICS	
2-5 YRS	SI MSI (GATES)* III-V DIODES (SIGNAL & POWER)* PASSIVES FOR IC'S* TRANSDUCERS BATTERIES HYBRIDS - 10,000 HR OPERATION	III-V TRANSISTORS* PACKAGING OF HYBRIDS	
5 YRS OR GREATER	SI LSI* MEMORIES*	III-V IC's* BATTERIES TRANSDUCERS* MEMORIES	ITC

* INSUFFICIENT MARKET FORCE MAY IMPEDE COMMERCIALIZATION.