

PROCEEDINGS OF THE SYMPOSIUM ON

# LOW TEMPERATURE ELECTRONICS AND HIGH TEMPERATURE SUPERCONDUCTORS

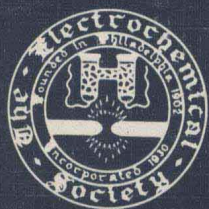
Edited by

Stanley I. Raider  
IBM T. J. Watson Research Center  
Yorktown Heights, New York

Randall Kirschman  
Mountainview, California

Hisao Hayakawa  
Department of Electronics  
Nagoya University  
Furo-Chō, Chikusa-ku  
Nagoya 464, Japan

Hiroshi Ohta  
The Institute of Physical  
and Chemical Research  
2-1 Hirosawa, Wako  
Saitama 351-01, Japan



*DIELECTRICS AND INSULATION DIVISION*

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THE ELECTROCHEMICAL SOCIETY, INC., 10 South Main St., Pennington, NJ 08534-2896

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## PREFACE

This Proceedings Volume includes papers that were presented at the Symposium on Low Temperature Electronics and High Temperature Superconductivity which was held during October 19-23, 1987 in Honolulu, Hawaii at a joint meeting of The Electrochemical Society and The Electrochemical Society of Japan in cooperation with The Japan Society of Applied Physics. Several papers on the same subject from a parallel Late News Paper session at this meeting are also included. The Symposium and this Proceedings Volume are sponsored by the Dielectrics and Insulation Division of The Electrochemical Society.

The included papers demonstrate that the study and use of low temperature electronics are increasing in many diverse areas, providing valuable benefits for many applications, as well as opportunities for research in materials and devices. Operating electronic devices and systems at low temperatures present many challenges for the designer and user. Although there is active interest in this area, it remains to be seen whether the advantages achieved by cooling electronics will lead to widespread practice.

Two recent developments, both discussed in this volume, have particularly focused attention on the field of low temperature electronics and could impact future applications. First, a supercomputer, the ETA-10, with its high speed VLSI processors populated with CMOS and cooled to 77°K during operation, was delivered to Florida State University and is presently being field-tested as it is brought up to its full operating potential. Secondly, superconductors with critical temperatures,  $T_c$ , in excess of 90°K were prepared by Chu et al. following the pioneering work of Mueller and Bednorz at the IBM Zurich Research Laboratory. Superconductivity can now be achieved at the same temperatures and with the same refrigerators used to cool semiconductor electronics. The consequences, from a user's perspective, of refrigerating the high speed processor of a supercomputer, and, secondly, high  $T_c$  superconductors and their possible role in electronics, are both discussed in these Proceedings.

The Proceedings, which is organized into six sections, contain 34 invited (designated by \* in the Table of Contents) and 28 contributed papers. The first section, "Introduction", contains three invited papers. The first paper by P.M. Solomon considers the application of low temperature electronics for VLSI applications. A second paper by T. Sugano summarizes work from Japan in low

temperature electronics. The third paper by D. Duke describes the status of the ETA-10 supercomputer, an important test case for supercomputer operation at low temperatures and considers the consequences, from a user's perspective, of refrigerating the high speed processor of a supercomputer.

Each of the remaining five sections is preceded by a section overview. The second section on "Low Temperature Microelectronics" consists of papers on silicon-based, liquid-nitrogen cooled, complementary MOS technologies for potential digital applications. The third section, "Refrigeration for Low Temperature Electronics", describes the methods of cooling electronics presently available for large and small applications. The fourth section, "Superconductivity and Superconducting Devices", provides a current report on high temperature superconductivity research, possible device applications, and the status of superconducting devices circuits, and processing using lower temperature superconductors. The fifth section, "III-V Compound Semiconductor Devices", describes improvements in heterojunction devices and new devices whose operation is improved at low temperatures. The sixth section, "Analog Characteristics and Applications", includes papers that deal with the properties and applications of a wide variety of semiconductor devices at frequencies from the audible to the visible. Experimental investigations of commercial and custom-made devices, with both discrete and integrated circuits, are represented.

A book on low temperature electronics was not available when this Symposium was initiated and it was our intent to make these Proceedings a useful resource book. Keeping with this aim, it is appropriate to note that one book in this field, Low Temperature Electronics, R.K. Kirschman (Ed.), IEEE Press, N.Y., 1986, and a journal issue, Special Issue on Low Temperature Semiconductor Electronics, IEEE Trans. Electron Dev., **ED-34** (January, 1987), were published in the interim. This Proceedings should be a useful, up-to-date supplement that includes topics not covered in these other publications.

Many people have assisted with the Symposium and the Proceedings Volume. We are particularly grateful to F. Bedard (NSA), R. Blaughter (Westinghouse), R. Brandt (ONR), R. Comizzoli (ATT), E. Edelsack (ONR), J. Mauer (IBM), M. Nisenoff (ONR), L. Rothman (IBM), and N. Welker (NSA); for suggestions and advice regarding the Symposium; to E. Edelsack (NRL), F. Gaensslen (IBM), R. Kiehl (IBM), K. Kitazawa (Univ. of Tokyo), T. Masuhara (Hitachi), B. Penswick (Sunpower, Inc.), W. Steyert (APD Cryogenics), G. Walker (Univ.

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S.I. Raider  
R.K. Kirschman

# CONTENTS

PREFACE .....	iii
I. INTRODUCTION .....	1
*Options for High Speed Logic at 77°K P.M. Solomon .....	3
*Low Temperature Electronics Research in Japan Takuo Sugano .....	18
*Use of the ETA-10 Supercomputer: A Status Report D.W. Duke .....	30
II. LOW TEMPERATURE MICROELECTRONICS .....	39
Overview - F.H. Gaensslen and T. Masuhara .....	41
*Low Temperature MOS Microelectronics R.C. Jaeger and F.H. Gaensslen .....	43
*Liquid Nitrogen Cooled CMOS T. Masuhara, M. Aoki, K. Yano, and S. Hanamura .....	55
*Low Temperature MOS Device Modeling S. Selberherr .....	70
*Cooling of Low Temperature Electronics W.A. Steyert .....	87
CMOS Devices Cooled with a Solvey-Cycle Experimental Refrigeration System M. Aoki, T. Masuhara, K. Matsumoto, K. Yano, H. Hasegawa, and T. Matsuda .....	93
Characterization of Cesium Oxide Implants for Use in MOS Devices Operated at 77°K B.J. Fishbein, J.T. Watt, and J.D. Plummer .....	102
Design Considerations for the Operation of CMOS Inverters at Cryogenic Temperatures M.J. Deen and J. Wang .....	108
* Invited paper	



On the Temperature Characteristics of Heavily Doped Polycrystalline Silicon Films J.D. Cressler, W. Hwang, and T.-C. Chen .....	117
Temperature Dependence of Required Refresh Time in Dynamic Random Access Memories P. Wynn, R.L. Anderson, and W.F. DesJardins .....	123
NMOS FET Gate Current Effects for Realistic Biases at 80 and 300°K A.K. Henning and J.D. Plummer .....	130
Comparison of Hot Carrier Degradation at 295 and 77°K N.S.Saks, D.M. McCarthy, and M.G. Ancona .....	136
Temperature Dependence of Charge Trapping and Dielectric Breakdown in MOS Devices S.A. Grot, C.-L. Huang and G. Sh. Gildenblat .....	142
Substrate Freeze-Out and Field-Dependent Donor-Acceptor Ionization in MOSFETs at Very Low Temperatures D. Foty and S. Titcomb .....	151
Modeling of Degraded MOSFET Due to Interface State Generation at Low Temperature Operation S.B. Bibyk, D.-C. Kau, A. Samman, and P. Roblin .....	161
Operation of CMOS Devices at 10°K S.B. Broadbent .....	170
Low Temperature MOS Device Characteristics I. Narita, H. Ohsuga and S. Matsumoto .....	177
Modeling of Temperature Dependent Transport Parameters for Low Temperature Bipolar Transistor Simulation M. Chrzanowska-Jeske and R.C. Jaeger .....	185
Needs and Possibility of Low Temperature Power Electronics Y. Murakami .....	200
 III. REFRIGERATION FOR LOW TEMPERATURE ELECTRONICS	207
Overview - W.A. Steyert .....	209
*Nomenclature and Classification of Cryocoolers G. Walker .....	211
* Invited paper	



*Survey of Cooling Techniques for Electronic and Sensor Devices C.K. Chan .....	219
*Refrigerators for Low Temperature Electronics W.A. Steyert .....	232
Free-Piston Stirling Cycle Cryocooler Development L.B. Penswick and W.T. Beale .....	241
*Integrated Cryogenic Chip Carrier for High Speed CMOS and Superconducting Devices W.A. Little .....	251
The Use of Automated Laboratory Test Equipment for the Characterization of Electronics at Cryogenic Temperatures C.N. Magoun .....	260
A Survey of Cryogenic Apparatus Available to Support Electronic and Electro-optic Studies Over the Temperature Range of 4.2K to 300K R.G. Hansen .....	267
IV: HIGH $T_c$ SUPERCONDUCTORS AND SUPERCONDUCTING DEVICES .....	
Overview - S.I. Raider .....	273
*Crystal Chemistry of the High $T_c$ Superconductors R.J. Cava .....	275
*Material Problems of Oxide Superconductors from Chemical Aspects K. Fueki, K. Kitazawa, K. Kishio, and T. Hasegawa .....	278
*Electric and Magnetic Properties of High $T_c$ Superconducting Oxide *Thin Films and Single Crystals T. Murakami, M. Suzuki, and Y. Enomoto .....	286
*Anisotropy in Single-Crystal $Y_1Ba_2Cu_3O_{7-x}$ W.J. Gallagher .....	297
*High $T_c$ Superconducting Thin Films and Applications R.B. Laibowitz, R.H. Koch, P. Chaudhari, G.J.Clark, R.J.Gambino, M.M.Plechaty, J.A.Lacey, C.P.Umbach, A.D.Marwick, and J.M. Viggiano .....	309
*Shapiro-Steps in Josephson Point-Contacts of Y-Ba-Cu-O Ceramics T. Yamashita, M. Takata, Y. Iwai, T. Komatsu and K. Matusita .....	318
* Invited paper	328

*Some Aspects of High $T_c$ Superconductivity: Exotic Properties, Applications to Electronics V.Z. Kresin .....	339
*Implications of High Temperature Superconductivity on Low Temperature Electronic Technology M. Nisenoff .....	344
*Superconductor-Semiconductor Hybrid Devices, Circuits, and Systems T. Van Duzer .....	352
*Advantages and Requirements of Superconductivity in a Future IC Chip P.M. Solomon .....	362
*High-Speed Josephson Digital Circuits S. Hasuo, S. Kotani, N. Fujimaki and T. Imamura .....	363
*Josephson Pseudorandom Bit Sequence Generator N. Fujimaki, T. Imamura, and S. Hasuo .....	375
*Measurements of a Vortex Transitional NDRO Josephson Memory Cell S. Tahara, I.Ishida, M.Hidaka, S.Nagasawa, Y.Ajisawa, and Y.Wada .....	381
Relaxation Oscillator for Switching and Local Oscillator Applications M. Muck, H. Rogalla, and C. Heiden .....	388
Nonlinear Superconducting Kinetic Inductance Microstrip for Devices and Circuits J.M. Pond and W.L. Carter .....	395
Cryogenic and Room Temperature Measurements of Niobium Nitride on GaAs E.J. Cukauskas, W.L. Carter, J.M. Pond, and H.S. Newman .....	401
Section V. III-V COMPOUND SEMICONDUCTOR DEVICES .....	409
Overview - R.A. Kiehl .....	411
*Self-Aligned Gate AlGaAs-GaAs Heterostructure FET Characteristics at Cryogenic Temperatures N.C. Cirillo, Jr., P.J. Vold, and D.K. Arch .....	412
*Performance of AlGaAs/InGaAs Pseudomorphic MODFETs at Cryogenic Temperatures T. Henderson, and H. Morkoc .....	424
* Invited paper	

*Advantages of Cooled Operation of Complementary Heterostructure FET IC's R.A. Kiehl, M.A. Scrontras, D.J. Widiger, and W.M. Kwapien .....	436
*Microwave and Millimeter-Wave Resonant-Tunneling Diodes T.L.C.G. Sollner, E.R. Brown, and W.D. Goodhue .....	443
*The GaAs Hot Electron Transistor W.P. Dumke .....	449
<b>VI. ANALOG CHARACTERISTICS AND APPLICATIONS .....</b>	<b>459</b>
Overview - R.K. Kirschman .....	461
*Low Temperature Behavior of 1/f and g-r Noise in Submicron Gate-Length GaAs MESFET's and Modulation-Doped FET's M.B. Das .....	464
Behavior and Comparison of RF Devices, Si JFET, Dual Gate MOSFET, and GaAs MESFET at 4.2, 77, and 300°K from the Point of View of Noise and GBW in the Frequency Range 10 kHz-50 MHz F. Celani, U. Gambardella, A. Giorgi, A. Saggese, S. Cata, and S. Pace .....	473
Low (1/f) Noise Metal-Gate PMOSFET's for Liquid Helium Operation P. Zappella, O. Griffith, Jr., K. Adams, J. Fuller, and J. Yee .....	489
*Cryogenic Electronics for Infrared Focal Plane Arrays D.H. Seib .....	499
Cryo CMOS Technology O. Kindl, W. Langheinrich, and G. Fischer .....	518
*Precision Thermometer with Cold Integrated Electronic System Using 15 Bit A/D Converter M.G. Rao and R.G. Scurlock .....	524
Cryogenic Preamplifiers for Precision Mechanical Measurements P.C. Moster, D.F. McQueeney, T.J. Gramila, and R.C. Richardson .....	529
High-Speed CMOS Multiplexer for Cryogenic Application Z. Szucs, R. Karunanithi, and U. Ruppert .....	537
Low Temperature Characteristics of CMOS Op-Amps M.J. Deen and K.C. To .....	545
Low Noise Cryogenically Cooled Broad-Band Microwave Preamplifiers B. Leskovar .....	554
* Invited paper	

*A Cryogenic 7 mm Receiver C.R. Predmore, G. McIntosh, and R. Grosslein .....	569
*Low Temperature Characteristics of Semiconductor Injection Lasers J. Katz .....	575
Low Temperature Operations of Silicon Charge-Coupled Devices for Imaging Applications B. Jaggi and M.J. Deen .....	579
AUTHOR INDEX .....	591
SUBJECT INDEX .....	593

\* Invited paper

## I. INTRODUCTION



## OPTIONS FOR HIGH SPEED LOGIC AT 77K

P.M. Solomon

IBM T.J. Watson Research Center,  
Yorktown Heights, N.Y.10598.

### *Abstract*

The role of low temperatures in improving the performance of digital logic circuitry has been expounded by several authors in the past. This paper will attempt a re-evaluation of these advantages in the light of recent advances in semiconductor technology and the added promise of the low  $T_C$  superconductors. Most of the advantages, on critical analysis, appear to be of limited leverage i.e. they are useful but not essential to the attainment of future high speed systems. The one area of critical leverage is the wires, both on and off chip. To the extent that the 77K environment is increasingly utilized for large, high speed computers, this paper will comment on which logic technology is most appropriate, and whether superconducting logic devices, if available, offer any advantages.

### *Introduction*

Even before the advent of the high  $T_C$  superconductors, the 77K environment has been considered by some researchers to be highly suitable for large digital computers. Indeed, ETA (1) has a supercomputer operating in the 77K environment for more than a year. Keyes (2) *et al.* have enumerated many of the advantages of the cryogenic environment and these have been expanded upon by Gaensslen *et al.* (3), Solomon (4), Matisoo (5), Coeure (6), Dennard (7), Dumke (8) and Abe *et al.* (9) among others. Much of the relevant material has been included in a book by R. Kirschman (10), and in ref. (11). For semiconductor devices at 77K the advantages are: 1) faster device operation 2) ease of device scaling 3) reduced power through lower voltage operation, 4) reduced wire resistance (including superconductivity now!) and electromigration, 5) increased thermal conductivity of the substrate. Along with these advantages come unpalatable disadvantages. These are: 1) the refrigeration burden 2) heat removal at the liquid-solid interface 3) thermal cycling, 4) testability, 5) freeze out and trapping of carriers, 6) enhanced hot-electron effects. In the following



sections we will re-evaluate some of these factors and determine their relative importance and which logic technology is the most suited to the 77K environment. While Si CMOS is the de-facto technology (1), other technologies based on III-V heterojunction devices (12) promise higher performances. Of the III-V materials, the GaAs - (Al,Ga)As materials system is the most mature technologically. Types of Heterojunction transistor are FETs (HFETs), Bipolar Transistors (HBTs) (13) and Hot Electron Transistors (HETs) (14). N-channel HFETs such as the modulation doped FET (MODFET) (15), semiconductor-insulator-semiconductor FET (SISFET) (16-18), and metal-insulator-metal FET (MISFET) (19), have demonstrated a very high performances at 77K. Complementary HFETs (CHFETs) (20) circuits have also been demonstrated. We will review the properties of these devices below. Superconductivity at 77K allows Josephson Junctions and other superconducting devices to be used. Will these prove to be superior to the semiconductor based devices?

#### A. Faster Logic Devices.

Semiconductor based devices improve in speed as temperature is reduced because mobilities and saturation velocities are higher. Most circuit delays in semiconductor logic are caused by the time to charge and discharge capacitors and are related to the currents and voltages by:

$$\text{delay} = C_{\text{device}} + C_w V/I \quad [1]$$

where  $C_{\text{device}}$  and  $C_w$  are the device and wiring capacitances, respectively. The delay is linked to the transit time  $\tau_t$  of the charge carriers through the device, where  $\tau_t = L/v$ ,  $L$  is the device length and  $v$  is the carrier velocity. This is because the current increases with carrier velocity and the capacitance increases with device length. For the FET in the long channel limit, the transit time is inversely proportional to mobility and is given by:  $\tau_t = L/(\mu V)$  where  $L$  is the channel length of the FET, while in the short channel limit it is inversely proportional to some maximum limiting velocity  $v_s$ , ( $\tau_t = L/v_s$ ) determined by the semiconductor properties. Mobility improves as temperature is reduced because of the reduction of phonon scattering (lattice vibrations) with temperature. This is especially dramatic for a GaAs modulation doped layer (see Fig. 1) where impurities have been separated from the carriers by the technique of modulation doping (21). Mobilities of  $> 3 \times 10^6 \text{ cm}^2/\text{V-s}$  have recently been reported at low temperatures. Bulk mobilities are given for various semiconductors in Table I, after Keyes (2). Mobilities in the channel of a field effect transistor are invariably lower than bulk, being reduced more in Si than in GaAs. Typical values are given in Table II. The high values of mobility obtainable especially in GaAs at low temperatures have a limited significance for short gate length FETs. This is for two reasons. Firstly, in small devices elec-

tric fields tend to be high, and the mobility decreases with field. This occurs when the electric field in the device is larger than the critical field as given by the ratio of the limiting velocity to the low field mobility. For FETs the electric field is determined by only a fraction of the supply voltage ( $\approx 1/4$ ) since conductivity of the FET is important in the low voltage state, and even more so for CMOS, where devices are connected in series. For GaAs FETs with a 1V power supply, the corresponding mobility would be  $1 \times 10^4 \text{ cm}^2/\text{V}\cdot\text{s}$ . Secondly, the mobility of an FET decreases when the channel length becomes shorter than the electron mean free path (22). This occurs in  $0.5\mu\text{m}$  devices for mobilities  $> 150,000 \text{ cm}^2/\text{V}\cdot\text{s}$ , which is roughly equal to electron mobilities in GaAs at 77K. Measurements made by the author on  $1\mu\text{m}$  heterojunction FETs at 77K give mobilities of  $\approx 3 \times 10^4 \text{ cm}^2/\text{V}\cdot\text{s}$ .

Maximum carrier velocities increase as well as temperature is lowered. The magnitude of the increase is not nearly as great as for mobility and is about 50% for GaAs (23) and 30% for Si (24) in going from 300K to 77K. The improvement of FET speeds will be bracketed by the improvements in mobility vs peak velocity depending on the ratio of voltage to channel length. Velocity overshoot in short channel length FETs has long been predicted (25), and should be more easily seen at low temperatures where electrons may more easily be accelerated by the field since they are not impeded by phonons. The issue of velocity overshoot for very short gate length FETs is still open. Even though both Si and GaAs FETs have been made with channel lengths down to  $0.1\mu\text{m}$  (26,27), no unambiguous demonstration of velocity enhancement has been seen.

A measure for the velocity in the channel of an FET, in the saturated velocity regime, is given by the ratio of transconductance per unit width to its capacitance per unit gate area. The transconductance per unit width is a useful figure of merit for the switching speed under heavily loaded conditions. Typical values of this ratio for some recently published devices are given in Table III for Si, GaAs and InGaAs channel devices at 300K and 77K.

Improvements in circuit speed will be related to improvements in device speed by eq. 1. Factors of improvement which have been reported are about 2x for silicon CMOS, about 1.5x for heterojunction FETs and about 2.5x for complementary heterojunction FETs. The latter large factor of improvement is due to the large increase in p-channel mobility from 400 to  $3200 \text{ cm}^2/\text{V}\cdot\text{s}$  (see Table II). Until recently the fastest semiconductor device was a modulation doped FET (MODFET) (28), operating at 77K with a delay of 5.5ps. This has now been bettered by the 5ps delay of heterojunction bipolar transistors (HBTs) at 300K (29). From this it may be inferred that raw speed cannot