Electronics with superconducting devices

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Superconducting devices are likely to lead to the development of new and improved electronic circuits and systems. Though the operation of these devices is likely to be at liquid nitrogen temperature, they will show several improvements such as low noise, high sensitivity, less degradation due to electro-migration and other thermal effects over the ones operated at room temperature. The main driving forces for the development of superconducting electronics are: high speed, low power consumption and high sensitivity. In this paper, development of superconducting electronic components is reviewed, specially in the light of the current research on high temperature superconductors. Present status on passive and active electronic components based on low temperature superconductors is also given. Microwave applications, digital high speed devices and circuits using passive superconductive components and Josephson junction are presented. Efforts to develop a transistor-like device are summarized. Work carried out in our laboratories is briefly reported. It is concluded that there is a great possibility of development of high temperature superconducting devices for low-noise, high-speed and low-power consuming electronic devices.

1 Introduction

Electronics with superconducting devices belongs to low temperature electronics, also known as cold electronics, cryogenic electronics or cryo-electronics, which involves operation of devices, circuits and systems at temperatures significantly below room temperature. The motivation for low temperature electronics is the improved performance compared to conventional electronics operating at normal ambient temperature. At low temperatures, the disruptive thermal effects that cause power waste, noise and wear-out are greatly reduced. The degradation and aging effects like corrosion, electro-migration and inter-diffusion, which increase exponentially with temperature, are also retarded by many orders of magnitude in devices operating at cryogenic temperatures.

The increased speed of digital systems, better signal-to-noise ratio and greater bandwidth of analog systems, improved sensitivity of sensors and greater precision of measuring instruments are some of the obvious advantages of cryo-electronics. The improvement in performance offered by cold electronics, ranges from a factor of two to several orders of magnitude and in some cases, it is only a few times of the ultimate theoretical limit. Owing to distinct performance benefits, researcher's endeavours are continued to develop cold electronics. In this connection, the uses of superconducting devices, which only operate at low temperatures, i.e. below their critical transition temperature ($T_c$) of superconduction, are being explored since the discovery of superconductivity in 1911. However, it is only after development of reliable niobium superconducting junctions towards the end of 1983, that various kinds of useful integrated circuits and systems, operating at liquid helium temperatures, were realized.

One of the major hurdles that prevented the wide use and rapid development of low temperature electronics is carrier "freeze-out" problem in silicon devices, which even todate constitute a major part of circuitry associated with a cryo-electronic system. At temperatures below about 40 K, silicon devices exhibit radical changes in characteristics due to carrier freeze-out, i.e. the current carriers in the devices become inactive in want of sufficient thermal energy. The recent discovery of high temperature ceramic superconductors having superconducting temperature above liquid nitrogen, has, however, opened up possibilities of raising the temperature of cold electronics to a level where associated semiconductor-based electronics also operates efficiently. Consequently, better performance is expected by combining matured semiconductor electronics with high $T_c$ superconducting devices. However, superconductive electronics can operate only below the material's critical temperature ($T_c$) of superconduction. Since superconducting properties improve as temperature is lowered, an operating temperature of about $(2/3)T_c$ or lower is preferred.
Therefore, for an electronic system, based on superconducting devices, to operate at liquid nitrogen temperature, a $T_c$ of about 120 K is desired. However, a standard two-stage mechanical cryo-cooler can reach easily 15 K and a system comprising liquid nitrogen superconducting devices and silicon devices can be envisioned to provide a hybrid low temperature electronics system, working efficiently at a temperature in the range of 40 K to boiling point of nitrogen.

In the present paper, superconductor-based low temperature electronics is briefly reviewed to reveal the added advantages of cryo-electronics with superconducting devices. Developments in liquid helium-based devices and systems are also described to bring out the potential applications of high $T_c$ superconductors. Finally, recent advances in high temperature superconductor (HTSC) devices and their applications to electronics are discussed. Work carried out in our laboratories is also presented briefly.

2 Superconducting electronics

Superconductivity is considered to be the most remarkable phenomenon of condensed matter physics. Two basic properties of superconductors are: (i) Zero DC resistance, below a certain transition temperature, i.e. perfect conduction and (ii) Meissner effect or expulsion of magnetic field in the superconducting state, i.e. perfect diamagnetism. The transition temperatures of known superconducting metals and alloys, now named as low temperature superconductors (LTSCs) are limited to 23 K, i.e. liquid helium temperatures. The new ceramic oxide superconductors, discovered in 1986, known as high temperature superconductors (HTSCs) have shown superconduction well above 100 K. This discovery of HTSC could bring the unique characteristics and benefits of superconductivity to a more practical domain and has the potential to cause great changes in the conventional cryo-electronics.

Since in the spectrum of general practical materials, there are no perfect conductors and diamagnets, the superconductors enjoy a unique category of applications. The influence of current, magnetic field and temperature on basic properties of superconductors is exploited to develop several active devices and passive components. However, the magnitude of superconducting properties is governed by the number of superconducting charge carrier pairs present in a superconductor. As the temperature is lowered, regular carriers, which co-exist with pairs, couple to increase the number of paired carriers. Thus, the superconducting properties of a material improve as temperature is reduced.

In general, the applications of superconductors are of two kinds. The first category is that of low-power electronic applications, where the involved current (only few mA) and magnetic fields (< 1 Tesla) are relatively small. The second class of applications employs bulk material in the form of wires etc. of large cross-section to support high current in high magnetic field environment. In the present paper we are concerned only with low-power electronic applications of superconductors.

2.1 Superconducting passive components

The criterion of zero resistance of a superconductor is no more valid at radio frequency. At these frequencies, surface current predominates and therefore, surface resistance ($R_s$) controls the high frequency behaviour of the material. For normal conductors, the current penetration depth is determined by ‘London penetration depth’. Since ‘London depth’ is small compared to ‘skin depth’, particularly at low frequencies, the thickness of a superconductor can remain very small at low frequencies and still it exhibits very low RF losses. The extremely low resistance of superconducting films at radio frequencies is valuable for microwave applications such as filters, low-loss transmission lines, ultra-high $Q$ resonators and other passive components.

A superconducting meander line, acting as a miniature transmission line, when combined with switches, could be used as an adjustable delay line for electronic counter-measure applications or as delay-compensating elements in wideband multifunction pulsed array. In distribution networks for antenna arrays, loss per unit length is a dominant factor and thus transmission line structure having the lowest possible effective dielectric constant is desirable. Using superconductor, a truly low-loss, low-volume distribution network could be realized.

The superconducting transmission lines can also store signal without much attenuation or distortion. On coupling with other devices, the lines can be configured to perform complex functions such as filtering, convolution, correlation, pulse compression/expansion, Fourier transformation and spectral manipulation. Circuits based on superconducting films have demonstrated real time analog processing of signals having gigahertz bandwidths that could be applied to radar.
communications or spectral analysis. Compared to circuits using normal conductors or based on surface acoustic wave (SAW) or acousto-optic techniques, superconductors can provide an order of magnitude greater bandwidth.

It is also natural to use superconducting films for interconnection on a semiconductor chip or to couple superconducting sensors at low temperatures to isolated semiconductor-based signal-processing circuits operating efficiently at a relatively higher temperature.

2.2 Superconducting active electronics

There is a wide range of active electronic circuits and systems based on Josephson junction (JJ), the foremost active device of superconductivity. The device possesses a number of attributes, such as fast switching, low power dissipation, wide frequency range, low noise and high sensitivity, which are valuable for electronic applications. The JJ digital gates switch rapidly within a few picoseconds and dissipate extremely low power (only a few microwatts). There is no semiconductor device that can match both at once. For example, a GaAs-MODFET matches speed but not power, while a Si-CMOS dissipates low power, but for low speed. Thus, digital systems and computers based on JJs could outperform those based on semiconductor devices. The following paragraphs briefly describe the JJ, since the superconducting electronics is primarily based on this device.

A high quality niobium-based JJ has been realized after the termination of IBM Josephson supercomputer programme in September 1983. The Nb/AIOx/Nb junctions are now frequently being used in almost all liquid helium-based cryo-electronics. This layered superconductor-insulator-superconductor (SIS) structure (shown in Fig. 1) is fabricated using conventional photolithography and thin film deposition techniques of semiconductor technology.

Current-voltage ($I$-$V$) characteristics of the junction are demonstrated in Fig. 2. For a thin dielectric layer (thickness smaller than electron pair coherence length), the junction exhibits Josephson effect, i.e. pair tunnelling without applied bias. Correspondingly, zero bias current called Josephson or critical current ($I_c$) is observed. For currents beyond $I_c$, voltage starts appearing across the junction. At a threshold voltage $V_g = 2\Delta/e$ (where ‘$\Delta$’ is the superconductor energy gap and $e$ the electron charge), the normal electron or quasi-particle tunnelling begins to dominate and an abrupt rise in current is observed above the threshold voltage as seen from Fig. 2. This normal electron or quasi-particle current gives rise to non-linearity in the $I$-$V$ characteristics and known as Giaever tunnelling.

Superconductor electronics with small number of JJs has seen an early success in practical applications. The magnetometer based on one or two JJs, called superconducting quantum interference device (SQUID), is the most sensitive instrument to detect extremely small magnetic field of the order of $10^{-10}$ gauss/(Hz)$^{1/2}$.

Josephson junction is a self oscillator, whose frequency is proportional to the voltage across the junction and is given by

$$f \propto (2e/h)V \quad \ldots \quad (1)$$

where, $2e/h = 483.6$ GHz/mV. Thus the voltage across a JJ is related precisely to the frequency. This can be used as a perfect local oscillator. Using a standard frequency source, this effect is being used as...
the basis of voltage standard since 1972. To obtain a practical voltage of 10V, ICs containing 104 JJs in series are irradiated at 90 GHz.

Perhaps the most impressive exploitation of JJs to high speed electronics technology is represented by the sampling digital oscilloscope and time domain reflectometry instrumentation of HYPRES INC. of U.S.A. This is based on niobium alloy JJ technology, realized on fused quartz substrates using 3 μm geometry. The HYPRES instrumentation achieves almost dispersionless transmission lines and reliable Josephson interferometers to produce PSP1000 workstation having rise time 5 ps, sensitivity 50 μV and bandwidth 70 GHz.

The non-linearity in $I-V$ characteristics of SIS junction (in Fig. 2) that onsets at the threshold voltage, $2Δ/e$, has been utilized to yield a very sensitive mixer for mm-wave and far infrared signals. For example, a noise temperature of about 15 K has been achieved near 100 GHz, which is only about two times the quantum limit. This noise performance is far better than that can be achieved by any other device. These Josephson SIS capabilities can be integrated with superconducting microwave passive components to create a superconductor version of MMIC to develop a high performance microwave receiver.

In computer applications of JJs, switching is generally accomplished by moving the operating point between the zero voltage (point A) and non-zero voltage (point B) states of the $I-V$ characteristics as depicted in Fig. 2. This can be achieved in two ways: (i) by applying magnetic field, and (ii) by injecting current. Accordingly, the Josephson logic gates are named as magnetic coupling gates or current injection gates. In magnetic coupling, the magnetic field generated by input signal current controls the gate, and current injection gates are operated by injecting input signal current directly into the gate. These two kinds of gates are configured in a number of ways to devise a variety of circuit building blocks (listed in Table 1) to achieve desired logic functions and to facilitate the fabrication of complex circuits. Among these, modified variable threshold logic (MVTL) gate, which is a hybrid version of these two, is widely being used in Josephson circuitry.

The operation of a Josephson logic gate differs from that of a semiconductor one. A Josephson gate switches in a latching mode, i.e. it does not return to its initial state after the input signal is turned off. A semiconductor gate maintains the changed state only when the input signal is applied. Thus a Josephson gate is biased by pulses rather than DC power and the pulse frequency determines the clock frequency.

<table>
<thead>
<tr>
<th>Classification of Josephson logic gates</th>
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<tbody>
<tr>
<td>Magnetic coupling gate</td>
</tr>
<tr>
<td>Single-junction</td>
</tr>
<tr>
<td>Multi-junction (SQUID)</td>
</tr>
<tr>
<td>Symmetric</td>
</tr>
<tr>
<td>Asymmetric</td>
</tr>
<tr>
<td>Current injection gate</td>
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<tr>
<td>Single-junction</td>
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<tr>
<td>Inductance coupling</td>
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<tr>
<td>SQUID</td>
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<tr>
<td>Junction coupling</td>
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<tr>
<td>Multi-junction</td>
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<tr>
<td>Resistor coupling</td>
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<td>Combination gate</td>
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</tbody>
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| JTL : Josephson Tunnelling Logic        |
| JIL : Josephson Interferometer Logic    |
| AIL : Asymmetrical Interferometer Logic |
| MAIL : Magnetically-coupled Asymmetric  |
| Interferometer Logic                    |
| CS gate : Current Switched gate         |
| CID : Current Injection Device          |
| HTCID : High Tolerance Current Injection Device |

| JTHL : Josephson Threshold Logic        |
| 4JL : Four-Junction Logic               |
| JAWS : Josephson Atto Weber Switch      |
| DCL : Direct Coupled Logic              |
| RCL : Register Coupled Logic            |
| REJL : Register Coupled Josephson Logic |
| VTL : Variable Threshold Logic          |
| MVTL : Modified Variable Threshold Logic|
The JJs have three important features for digital applications: (i) high switching speed (1-10 ps/gate), (ii) low power consumption (1-10 µW/gate), and a low dispersion signal transmission (transmission velocity is 100 µm/ps). The development of high speed superconductive computing system is attributed to these three important characteristics of a JJ. Experimental digital ICs based on JJ are typically five times faster and dissipate one hundredth the power of equivalent semiconductor ICs operating at room temperature. Although the low temperature semiconductor ICs are equivalent or better in speed to JJ circuits, nevertheless the low power advantage of JJs is unparalleled. This is one of the major issues which is limiting the packing density in modern Si-VLSI.

Device dimensions in JJ circuits have feature sizes comparable to those of their semiconductor counter-parts and likewise incorporate resistor, capacitor and inductors. Their fabrication technology is same as that of semiconductors wherever it is possible. However, special developments are needed because of differences in materials, devices, and circuits.

In addition to the difficulties in materials and process development, device design and circuit simulation, progress in superconductive electronics is hindered by lack of a good active device like transistor. To obtain the basic functions, several JJ configurations are used in a superconductive digital circuit. Unfortunately, none of the schemes matches the three-terminal transistor, in which important advantages of input-output isolation, well-defined gain and inversion are inherently available.

Thus, building a practical electronic system such as a computer from JJ devices is more challenging than one from semiconductor devices. Nonetheless, a JJ-based microprocessor has been developed by Fujitsu, Japan; although no complete superconducting computer has yet appeared. Scientists at Fujitsu laboratories employed Nb/Alo.X/Nb JJ to fabricate MVTL gate family, i.e. OR, AND and 2/3 majority gates. Using this gate family, they fabricated 16-bit ALU (Arithmetic Logic Unit), 8-bit shift register, 4-bit microprocessor and a 4-bit signal processor.

Fujitsu 4-bit microprocessor is the first example of applying Josephson devices to verify the feasibility of the chip in comparison with AM2901 microprocessor of Advanced Microdevices Inc., USA. It has minimum device feature of 2.5 µm and interconnecting line of 4.0 µm width. A total of 1841 MVTL gates are realized on the chip to accomplish all the desired functions. The microprocessor circuit confirmed operation up to 770 MHz clock frequency, consuming a total power of 5 mW, i.e. 3.6 µW/gate. Thus, it showed significant improvement in performance over that of silicon (30 MHz at 1.4 W) and GaAs (72 MHz at 2.2 W).

A 4-bit signal processor was also realized in Fujitsu laboratory by extending the microprocessor. A 4-bit multiplier, a 12-bit accumulator, a 8-K bit ROM and a sequencer were added on a chip of size 5 × 5 mm². In this case, the feature size was reduced to 1.5 µm to accommodate 3056 gates. The circuit exhibited clock frequency of 1.1 GHz and dissipated 6.1 mW of the power. Fujitsu scientists also reported their success with fabrication of memory circuit up to 4-K bit with 0.5 ns access time.

3 High temperature superconductive electronics

Soon after the discovery of superconduction in ceramic oxide in 1986, a large number of cuprate oxide compounds were synthesized in search of a superconductor having highest possible temperature of superconduction. Consequently, the compounds based on oxides of Y:Ba:Cu; Bi: Sr:Ca:Cu and Ti:Ba:Ca:Cu have been established as high temperature superconductors with critical transition temperatures in the range of 77-140K.

In the preceding section, we have reviewed circuits and systems incorporating low temperature superconductors. However, the majority of current research efforts are directed towards the use of high temperature superconductors to substitute devices and components based on conventional low temperature superconductors and metals. This needs understanding of intrinsic properties of HTSC materials and an appropriate technology base to realize HTSC-based devices and components. In the following sections, some of the key criteria are discussed to elucidate the performance benefits and limitations of HTSC-based devices, and their applicability to electronics are subsequently summarized.

3.1 Cryogenics

One of the major impacts of using liquid nitrogen as coolant in field applications is the drastic reduction in maintenance cost of its cryogen compared to conventional liquid helium cryostat. This is attributed to the difference in their latent heats. The latent heat of liquid nitrogen (LN₂) is about 60 times that of liquid helium (LHe). Therefore, the boil rate of LN₂ is much slower than LHe. Consequently, it is easy to design an LN₂ cryostat with hold times of up to one year and, therefore, it is highly economical to maintain a system operating at liquid nitrogen temperatures.
As discussed earlier, a semiconductor-superconductor hybrid system is preferred to be operated above 40 K (i.e. semiconductor carrier freeze-out temperature) but below transition temperature of superconducting devices (two third of \( T_c \), to derive maximum performance benefits of both the technologies. This can be easily implemented using 77 K superconducting devices with liquid neon (LNe) as a coolant or employing a standard two-stage mechanical cryo-cooler. It is important to note that latent heat of LNe (b.p. 28 K) is about 40 times that of liquid helium. Therefore, use of LNe as coolant would also greatly extend the running time over that of LHe. Thus the operational cost of a HTSC-based electronic system is much lower compared to a conventional cryo-electronic system which necessitates either liquid helium or a complicated refrigeration stage of Joule-Thomson loop to achieve temperatures below 15 K.

3.2 Thin films

The two important parameters that determine applicability of superconducting films to electronics are their current carrying capability and surface resistance. A representative set of data on critical current density \( (J_c) \) for good films is shown in Fig. 3. The \( J_c \) that has been achieved so far in Y Ba CuO films is quite high, typically \( 5 \times 10^6 \) A/cm\(^2\) at 77K. Bismuth cuprate films are comparable to Y Ba CuO, whereas current density observed in thallium films are comparatively lower by more than an order of magnitude.

A wide variety of measurement results of surface resistance \( (R_s) \) on HTSC bulk, thin films and single crystals are depicted in Fig. 4. It can be seen from the results that, for microwave and mm-wave applications, HTSC thin films are the most promising materials. At 100 GHz, the films have \( R_s \) values just lower than copper, but at 10 GHz, even the patterned films are one or two order of magnitude better than copper.

It is observed from the results shown in Figs 3 and 4 that the critical current density and surface resistance of in situ prepared superconducting film are better than those of post annealed films. Thus both these parameters are believed to be dependent on surface smoothness and grain size of the films. Given the fact that HTSCs are rather recent candidates, the results on \( R_s \) and \( J_c \) achieved to date are significant and a hope for further improvement by an order of magnitude is not unreasonable.

3.3 Microwave applications

The low RF surface resistance has accelerated the applications of HTSC for signal processing and microwave components. Co-strip lines capable of propagating very short pulses have been tested. A microstrip transmission line formed by sandwiching a mylar dielectric between two HTSC films has been operated from 2 to 25 GHz (Ref. 3). The HTSC resonators at microwave frequencies have been reported to exhibit high \( Q \) compared to that of copper. Microwave HTSC antennas have demonstrated improved performance at 77 K as compared to conventional copper antennas.

An important aspect needed to be considered for microwave application is the dielectric loss. Therefore, the substrates on which HTSC films are prepared should have low dielectric constant. Currently MgO, La Ga O\(_3\) and La AlO\(_3\) appear promising in this respect. Semiconductor like GaAs is also a favourable material for substrates, but it necessitates a low temperature process for fabrication of superconducting films. Therefore, superconducting films on a variety of substrates are required for the wide range of microwave applications.

For both hybrid circuits and hybrid systems, a popular proposal is to use superconducting interconnections between individual semiconductor transistors on an integrated circuit chip or between chips. This is to increase speed in digital circuits, as signal can propagate along a matched superconducting line without loss or dispersion for frequencies less than the gap energy. Thus HTSC transmission line provides an ideal means to transmit fast pulses with rise-time less than 10 ps. For on-chip interconnections, the use of superconductors does
not show a clear benefit, since circuit delays are dominated by driving resistances rather than interconnection impedance. Nonetheless, for larger chips with longer lines of smaller cross-section, this approach may be warranted to achieve higher speed. Similarly a Josephson CPU or highly sensitive detector operating at 4.2 K can be connected to a CMOS memory unit or HEMT device cooled to 77 K using HTSC interconnects.

Recently a mm-wave receiver system has been proposed as a possible semiconductor-superconductor hybrid system. The antenna, input filter, local oscillator, mixer, analog, signal processor and A/D converter could profitably use superconductor technology. The IF amplifier and memory unit could exploit the advantages of semiconductor devices. It may also be possible to use superconducting devices for part of the processor.

Such receiver system appears to be an excellent example of hybrid applications, because unique features of both the technologies are exploited in this. For example, the frequency of Josephson oscillator can be very accurately and conveniently tuned by applied voltage. Superconducting antenna and filter could have lower losses and higher quality factors than normal metals. The amplification and complex digital processing are obviously inherent strengths of semiconductor technology.

3.4 Digital applications

We know that high speed superconductive digital electronics is primarily based on SIS JJ. Unfortunately, the technology for fabrication of SIS structures in HTSC materials is yet to be evolved. Due to high processing temperatures, the insulating barrier does not maintain integrity in HTSC junctions. Therefore, a low temperature process and alternate insulating materials are actively being explored to develop a viable technology to realize HTSC logic gate based on SIS JJ.

However, grain boundaries inherently occurring in HTSC films have exhibited Josephson tunnelling effect. Consequently, SQUIDs operating at 77 K have been realized in all the three (yttrium, bismuth and thallium) cuprate superconductors. The performance of 77 K HTSC SQUID has been reported to be at par or even better in some cases than that of LTSC devices at 4.2 K.
The application of HTSC JJ to digital electronics requires considerations of some operational parameters. For example, the operating voltage of a Josephson logic gate is determined by gap energy of the superconductor and it is about 3 mV for Nb/AlOx/Nb junction. Since it is proportional to transition temperature, the operating voltage of HTSC gate would be 30 mV (as $T_c$ of Nb is 9 K and that of HTSC is 90 K).

Further, since the thermal noise is proportional to $\exp (-\frac{hI_c}{e kT})$, the critical current $I_c$ should be increased proportionally to the operating temperature to avoid erroneous operation due to the thermal noise. For example, at 4.2 K, a Nb gate operates between 0.1 to 0.5 mA, so that a HTSC junction at 77K must operate in the range of 2 to 10 mA. Consequently, power consumption of a HTSC gate becomes 200 times larger than the conventional LTSC gates.

The switching time of the logic gate is determined primarily by $RC$ time constant, where $R$ is the impedance of strip line, which is usually chosen to match the tunnelling resistance and $C$ is junction capacitance. Since in case of HTSC, grain boundaries are tunnelling junctions, we do not know the exact value of $C$. Considering it to be the same as in case of Nb/AlOx/Nb junction, and since $R$ is also unchanged because current and voltage increases by the same amount, the switching speed of HTSC gate is almost the same as that of Nb junction. We, therefore, can expect high speed for HTSC gates, but the circuit size will be restricted by their higher power consumption.

However, with the aid of sub-micron and nano-lithography, which is available in semiconductor technology, it is hoped that fabrication of JJ with extremely small dimensions would be possible. Even then, the development of high current-density thin film of HTSC material and their compatibility to the right kind of substrates are very essential. The current status of $J_c$ of high $T_c$ films and the research trends in this area suggest that HTSC gates with performance equivalent to niobium devices, if not more, are likely to become viable in the near future.

3.5 Superconducting transistor

The motivation for developing three terminal superconductive device has been to improve upon the gain and isolation and to provide an active device like semiconductor transistor for digital and analog applications. A number of schemes of three-terminal semiconductor-based superconducting transistor have been conceived, but which device will make its way into practical superconductor electronics has yet to be determined.

Basically the proposed devices are of two kinds. In a FET type structure, superconducting source and drain are formed in a semiconductor substrate$^4$-$^7$. In this device, proximity effect is utilized to obtain transistor characteristics. Recently such a transistor has been realized at Hitachi Lab., Japan$^8$, with a hope to obtain a three-terminal superconducting device having high speed and low power dissipation.

Another type of three-terminal structure which has been envisaged is superconducting base semiconductor isolated transistor (SUBSIT), analogous to bipolar transistors$^9$-$^{10}$. In this device, superconducting bipolar junctions are the majority and quasi-particles are the minority carriers in the base. This transistor shows promise in terms of high frequency operation owing to low resistance superconducting base. However, realization of the structure needs a true ohmic contact between the base and isolator, thus imposes a severe demand on technology.

These structures have not yet been reported to be fabricated in HTSC materials. The small coherence length of pairs in this material, which determines the gate length of transistor, and the technology of HTSC films on appropriate substrates material may be possible reasons for this. However, recently, Hashimoto et al.$^11$ have fabricated a slightly different kind of FET structure in thin films of YBaCuO superconductor. In that structure, the channel, which connects source and drain electrodes was also made of HTSC material unlike that of semiconductor in the proposed FET. Aluminium metal gate is employed to control transport across the source drain. The device has exhibited FET like characteristics at 4.2 K.

4 Our high temperature superconductivity research

Our efforts aim at the development of superconducting three-terminal devices in HTSC materials for microelectronic applications. We have developed a simple spin-on technique to fabricate superconducting films of HTSC materials. We have prepared thin films (less than one micron thickness) of lead-doped bismuth cuprate on MgO, with $T_c$ of 82 K and $J_c$ of 600 A/cm$^2$ at 77K. Using conventional photolithography and chemical etching we could generate micro-patterns in these films.

To explore device applicability of these films, DC SQUID structures are fabricated as shown in Fig. 5(a). The device showed Josephson tunnelling at 77K and quantum interference effect at 4.2 K. The device is housed in a plastic package as shown in a photograph of Fig. 5(b) (Ref. 12).
We have attempted to fabricate FET structure. The aluminium gate of the structure (Fig. 6) is formed by lift-off technique. Although the device dimensions are large, yet our initial efforts illustrate the possibilities of a viable process of fabrication. We are hopeful of fabricating such devices with required dimensions (near a micron).

5 Conclusions

This paper briefly reviews superconductor-based low temperature electronics. The primary motivation for low temperature operation is to bring out the ultimate performance from devices, circuits and systems which is superior to room temperature operation of conventional electronics in several aspects.

It is evident from the study that in terms of speed and power consumption, superconducting devices possess a clear edge over their semiconductor counterpart. Semiconductor devices also do not match the low-noise and high-sensitivity performance of superconducting devices. However, for digital processing, no substitute exists for semiconductor devices. The strength of semiconductor electronics lies in its three-terminal transistor device which provides all the required functions, an excellent input-output isolation and high gain.

Although the feasibility of Josephson transistor has been demonstrated, nevertheless, it is clear that a useful superconducting transistor is yet to come. Until a three-terminal superconducting device like semiconductor transistor appears, it seems difficult for cryo-electronics to function without semiconductor devices. Therefore, the present status of hybrid semiconductor-superconductor electronics is likely to continue till such a breakthrough occurs.

Undoubtedly, the temperature range of HTSC has generated great excitement, particularly, to provide an optimum combination of semiconductor-superconductor electronics as now it has become possible to operate at a temperature which is both above the semiconductor carrier freeze-out point (i.e. 40 K) and below superconducting transition temperature of HTSC. Nonetheless, considerable developments are needed to realize HTSC-based devices. The expectation in
this regard is not unreasonable, particularly in view of progress made in the last few years. Several new applications would be discovered for the HTSC devices depending on their unique characteristics.

While it is natural to consider which of the conventional applications might be exploited with HTSC, it would be worthwhile to use unusual characteristics of copper oxide materials, e.g. smaller coherence length, larger energy gap and higher upper critical field to explore newer applications and devices.

References