RECENT RESULTS ON: SURFACE-CHANNEL SCHOTTKY, InGaAs SCHOTTKY, AND Nb BASED SIS MIXER ELEMENT RESEARCH+

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ABSTRACT

The Schottky barrier diode is the mixer element of choice for heterodyne receivers operating at frequencies in excess of 100 GHz and above superconducting transition temperatures. While ground based systems can tolerate a whisker contacted structure due to its minimum value of shunt capacitance, space based systems require the mechanical integrity of a whiskerless structure. The Surface Channel Diode, a new structure which exhibits simplicity of fabrication along with minimum parasitic element values, will be reported upon. Both DC and RF performance will be presented.

GaAs has been the material of choice for Schottky barrier mixer and varactor diode fabrication for the past 20 years. As frequencies of operation reach the terahertz range the need for less LO power and lower mixer temperature become more severe. The InGaAs system offers great promise in relaxing these needs due to its lower barrier potential and higher electron mobility. Preliminary results obtained in an investigation of the use of InGaAs in Schottky barrier fabrication will be reported upon.

The promises of conversion gain, quantum limited noise, and minimal LO power requirement are held for SIS mixer elements. Recent calculations indicate Nb elements should operate well past 1 THz with only minimal degradation. Niobium based trilayer research which has produced devices exhibiting excellent electrical results (Vm > 1.5V, and extremely low sub-gap leakage current) will be described.

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1. INTRODUCTION

The needs of high sensitivity heterodyne receivers of the future operating at frequencies in excess of 100 GHz are dependent on the receiver operating temperature. Those operating above the critical temperature, Tc, of operational superconducting materials will require semiconductor diodes exhibiting highly nonlinear electrical parameters as mixing elements; while those operating at temperatures below Tc will require superconductive elements. At present, the semiconductor element of choice is the Schottky barrier diode. and the superconductive element having yielded the best receiver results to date is the superconductor-insulator-superconductor, SIS, junction. This paper treats device requirements and recent results obtained in each of these areas at the University of Virginia Semiconductor Device Laboratory.

Submillimeter wave applications of Schottky barrier mixer diodes will require a device devoid of contact with a sharpened metal wire, a whiskerless diode, for ease of integration into subharmonic mixers, MMIC's, and imaging arrays. Also required will be a diode needing a minimum of LO power due to its attendant scarcity with increasing frequency. Our most recent advances in the whiskerless diode technology are presented in Section 2. A report on research toward lowering needed LO power by reducing diode forward turn-on voltage is presented in Section 3.

Superconductive mixer elements must exhibit a minimum value of sub-gap current, an abrupt change in conductance at the gap sum voltage, minimum proximity effects, excellent mechanical robustness, immunity to change with temperature cycling, and the highest possible gap frequency. At this time SIS elements yielding the best DC and RF results and the greatest promise are those employing Nb or NbN. Results on a Nb/Al_2O_3/Nb trilayer technology and a NbCN edge-junction technology, both yielding excellent electrical characteristics, are presented in Section 4.

2. THE SURFACE CHANNEL DIODE

Certain radio astronomy applications requiring optimum performance in the THz range will tolerate whisker contacted diodes. The vast majority of receivers utilizing Schottky diodes, however, will require the mechanical integrity of whiskerless structures. This will be especially true of receivers employed in space, balloon, and airborne applications. In addition to mechanical rigidity, such device technology can provide ease of integration into MMIC's and arrays for imaging applications.

Work on whiskerless diodes has been ongoing for approximately 15 years. M. V. Schneider of Bell Labs was one of the early contributors to the beginning of this work (1) and to whiskerless diode investigation in general (2). An article by Garfield (3) on the RF testing of the device of this section, the surface channel diode, presents a rather complete listing of the papers pertinent to this topic. Cross-section and isometric views of a general whiskerless diode are shown in Fig. 1.

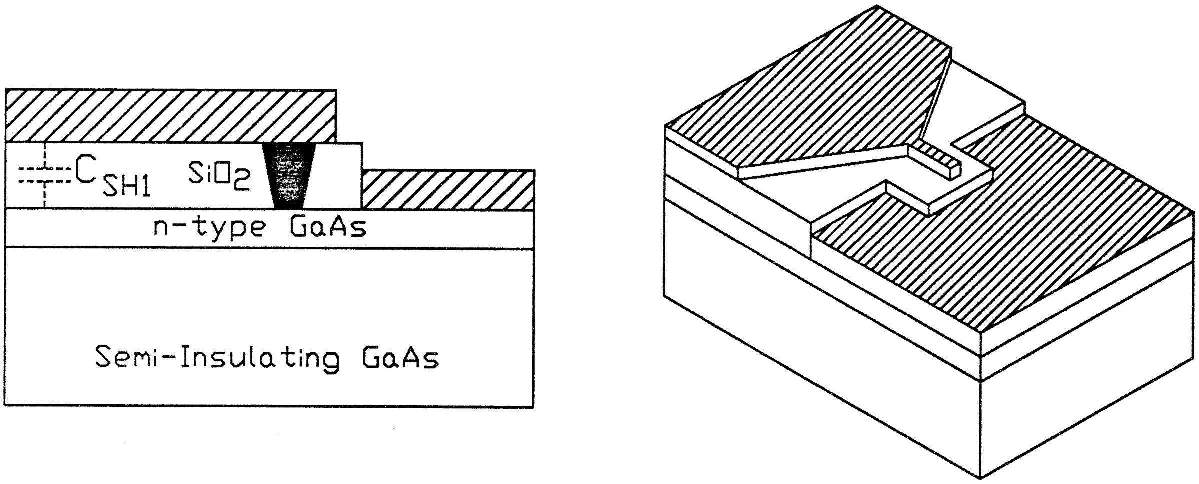

Figure 1 A general whiskerless Schottky diode structure.

The shunting effect of the conducting GaAs layers underlying the anode contact area and connected to the cathode presents a severe limitation at high frequencies. Several fabrication techniques have been employed in an attempt to lessen this effect and are shown pictorially in Fig. 2.

Bishop(4) recently presented an innovative approach[1] which results in the surface-channel diode shown in both pictorial cross-section and SEM views in Fig. 3.

This surface-channel technology is felt to be superior to the others in that it is straightforward, less costly, and yields a planar device. Relative disadvantages of the other

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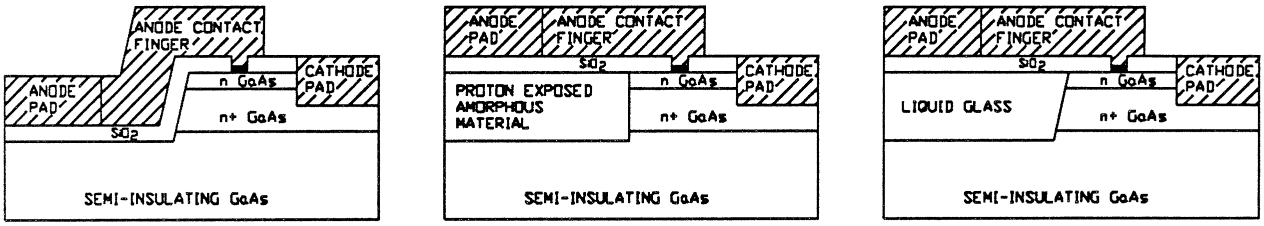
[1] NASA patent application case no. GSC 13063-2CU



MESA PROTON ISOLATED LIQUID GLASS

Figure 2 Pictorial views of (a) mesa, (b), proton isolated, and (c) liquid glass whiskerless diode structures.

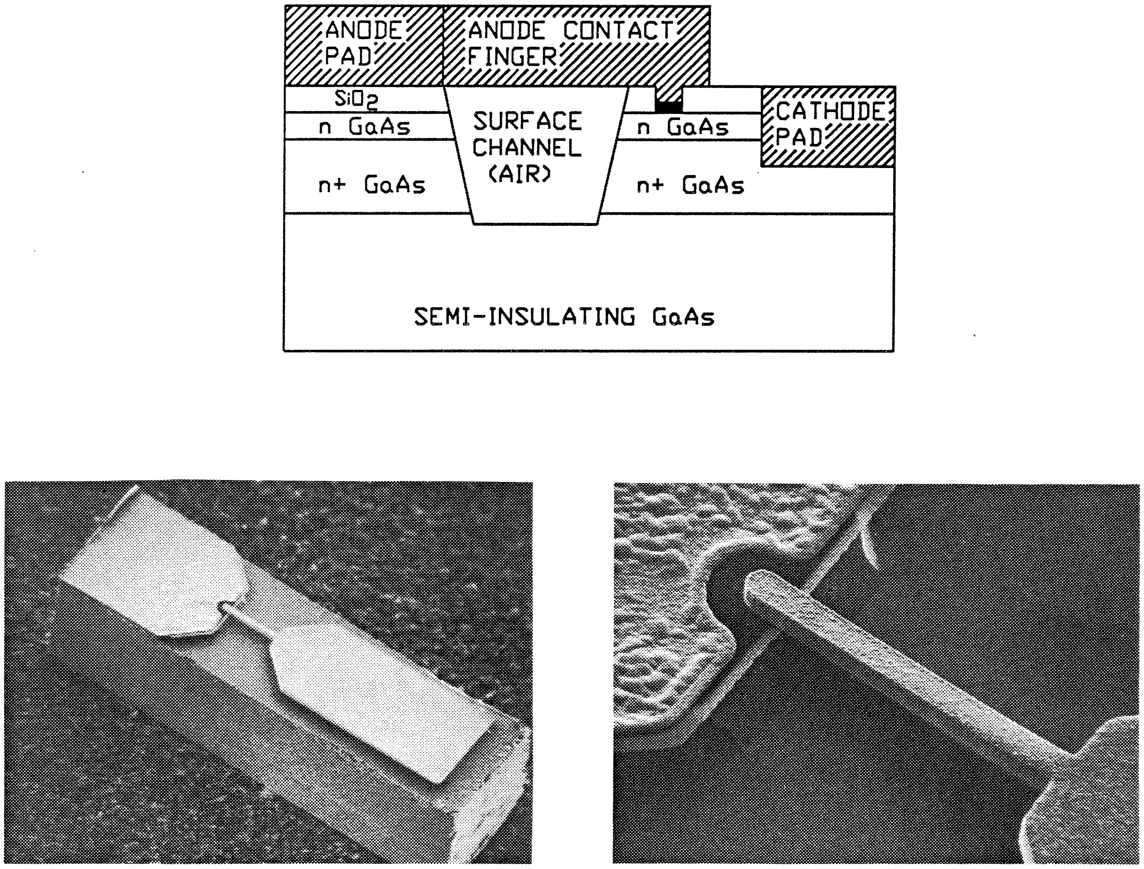


Figure 3 Surface-channel diode structure shown in pictorial cross-section and SEM views.

mentioned technologies are: the non-planar nature and resulting lack of precise photolithographic definition in the case of the mesa device, the added complexity of the proton bombardment process, and the intolerance to gross temperature change of the liquid glass isolated device.

A further extension of the surface-channel technology which permits complete removal of the substrate or its replacement with a lower dielectric material will be presented by Bishop(5). This advancement, which we feel brings the hybrid technology to its ultimate limit, is presented along with the basic surface-channel technology in the following section.

2.1 Fabrication Technology. Not only does the surface-channel technology yield a novel method for isolating devices, or device sections, on the same semiconductor substrate; but also it is quite straightforward. The four basic processing steps required for formation of a surface-channel Schottky barrier diode are shown pictorially in Fig. 4. Here the surface channel separates the anode contact pad from the junction region thus greatly reducing the capacitance shunting the junction. This disconnects the shunt capacitance, Csh1, (Fig. 1) from the Schottky diode region. Another advantage of this technology is that the surface channel is formed in the last step of the process thus allowing previous lithography steps to be carried out on a planar surface. The advantage can be appreciated from Fig. 3.

2.2 Electrical Performance. We found no substantial difference, with the exception of the shunt capacitance, between the standard whisker-contacted diode and its surface channel counterpart. Measured electrical parameters for diodes from two surface channel batches and for a whisker contacted diode, having nearly the same diameter and formed on GaAs of nearly the same donor concentration and layer thickness, are presented in Table I.

The only substantive difference between diodes of the two technologies is shunt capacitance. Figure 5 shows pictorial and circuit schematic representations for a surface-channel diode along with approximate capacitance values for 2.5 micrometer diameter test device.

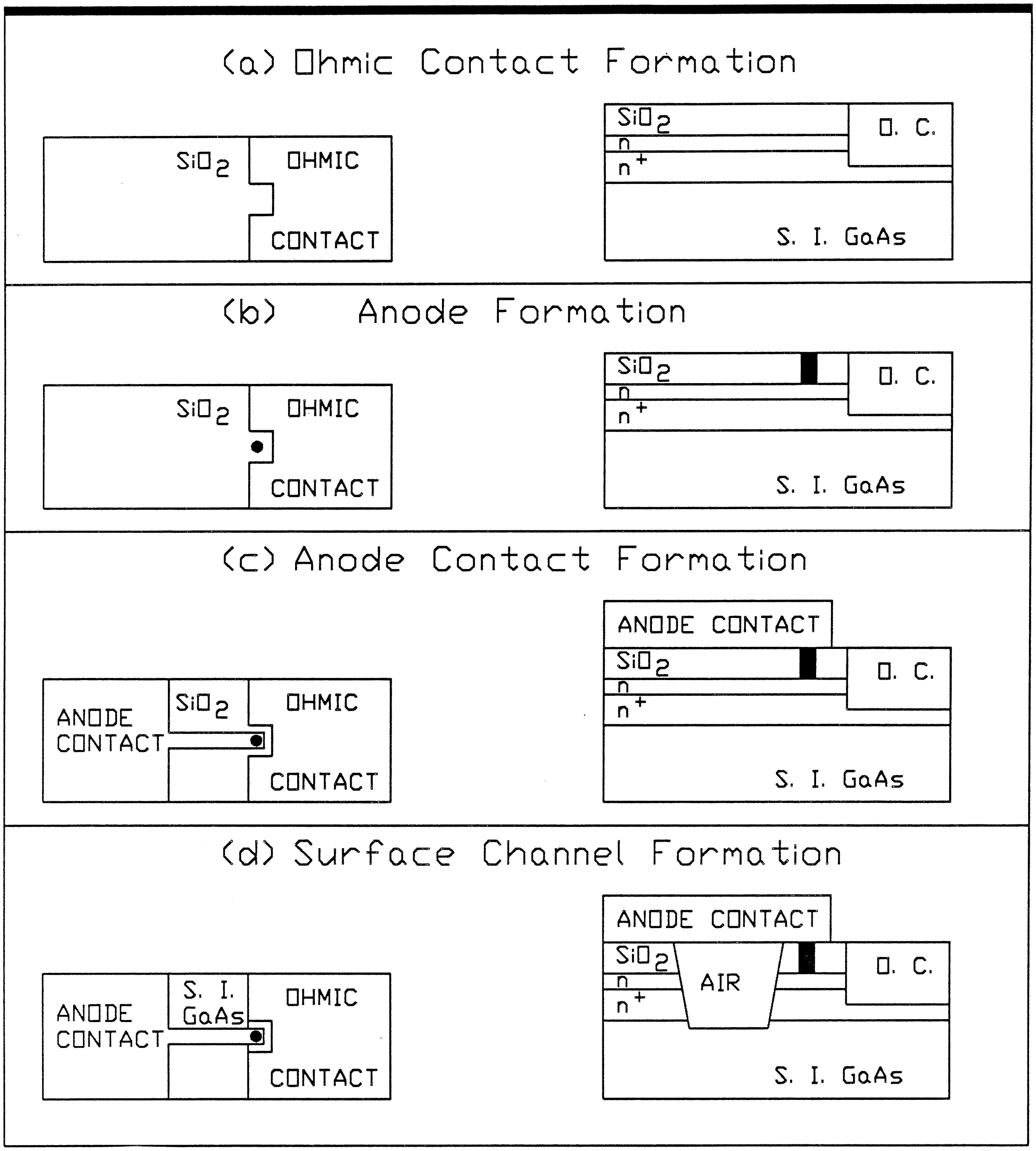
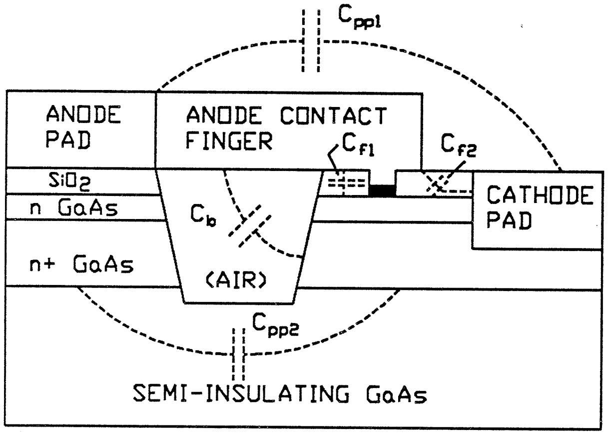


Figure 4 Surface-channel diode fabrication steps: (a) ohmic contact formation, (b) anode formation, (c) anode contact formation, and (d) surface channel formation.

Table I

Electrical Parameters of Surface-Channel and Comparable Whisker-Contacted Schottky barrier Diodes.

	Surface-Channel (SC2R4)	Whisker Contacted (2P14)
Diameter (μm)	2.5	2.3
Rs (ohms)	5.4	4.4
Δ (mV)	70	69
Cj (fF)	6	7
V_{br} (V)	6.2	6.2



$$C_{PPT} = C_{PP1} + C_{PP2} \cong 8.6\text{fF}$$

$$C_b + C_{f1} + C_{f2} \cong 1.7\ \text{fF}$$

Figure 5 Pictorial and schematic diagrams for a surface-channel diode. Capacitance values are for a 2.5 micron diode structure.

In the case of the surface-channel diode the importance of the pad-to-pad capacitance is mount dependent. That of an isolated device may well become a part of the RF circuitry (e.g. as part of a coplanar waveguide circuit) once the device is mounted. Thus the beam capacitance, Cb, and the finger capacitance, Cf, are the shunt elements of importance. This total shunt capacitance value has been shown to be on the order of 1.7 fF for a specific 2.5 micrometer diameter test diode structure. Furthermore this value was shown experimentally to decrease by approximately 1 fF upon removal of the SiO_2 surrounding the anode. This resulting value of approximately 1 fF is very near that of a comparable whisker contacted diode as shown by Kerr et al.(6), and leads to the conclusion that the surface-channel structure holds great promise for application in the THz frequency range.

Characterization of test surface-channel structures at 100 GHz was carried out by Garfield (3) using a technique similar to that of Weinreb and Kerr (7). Mismatch at both RF and IF ports was taken into account and harmonic conversion was shown to be negligible. Device DC excited noise temperature was shown to be comparable to that of an equivalent whisker contacted device which performed well in room temperature mixer applications. Mixer conversion loss and noise temperature performance were also found to compare favorably with the best obtained at room temperature in that frequency range with whisker contacted diodes as is shown in Table II.

Table II

Mixer noise temperature and conversion loss at 94 GHz for comparable surface-channel and whisker contacted diodes.

Diode Type	Tmixer (SSB) @94 GHz	Lmixer (SSB) @94 GHz
Surface-Channel (SC2R1)	555 K	5.8 dB
Surface-Channel (SC2R2)	518 K	5.3 dB
Whisker-Contacted (2D2)	560 K	5.3 dB

2.3 Substrate Replacement/Removal. Use of any conventional whiskerless diode in a hybrid application will cause a disturbance of the field pattern surrounding the transmission structure due to the diode substrate. A GaAs substrate with a dielectric constant of 13 would cause an even greater disturbance than would a quartz substrate with a dielectric constant of 3.8. Scale model studies have shown that the pad-to-pad capacitance of such a device can be reduced by a factor of ten by elimination of the GaAs substrate. It was this realization which prompted the development by Bishop(5) of a practical and simple method of device substrate replacement or removal.

This novel technique[2] involves fabrication of the device, removal of the original semiconductor substrate, and bonding of the remaining epitaxial layers to a replacement substrate of lower dielectric constant such as quartz. Its basic steps are depicted in Fig. 6. This process yields a single device or multiple device configuration attached to a replacement substrate by an adhesive layer, A2. Resulting devices can then be easily manipulated and bonded into circuits as desired. The final step, if desired, is the removal of the replacement substrate by dissolution of adhesive layer, A2. This step results in a device layer consisting of metallization and semiconductor material only a few microns thick bonded into the microwave integrated circuit. Figure 7 shows a photomicrograph of a Schottky barrier diode bonded into a circuit and the substrate removed by this process.
The resulting structure consists of a 80x175 micron anode contact metallization pad connected by a 4x50 micron gold beam to a Schottky anode. That anode is formed on a two micron thick layer of single crystal GaAs which also bears an alloyed 125x125 micron ohmic contact pad.

In summary, the surface channel technology provides a simple, straightforward method of fabrication of Schottky barrier mixer and varactor diodes exhibiting excellent electrical characteristics, excellent mechanical stability, ease of integration into MMIC's, and reduced shunt capacitance. In addition, the substrate replacement/removal technology yields near monolithic integrated circuit results while maintaining the flexibility of hybrid technology. These two technologies provide a means of producing Schottky barrier diodes which meet or exceed the above mentioned needs of whiskerless diodes. The one remaining need, reduction of the forward turn-on voltage of the mixer diode, is addressed in the next section.

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[2] NASA disclosure case no. GSC 13205

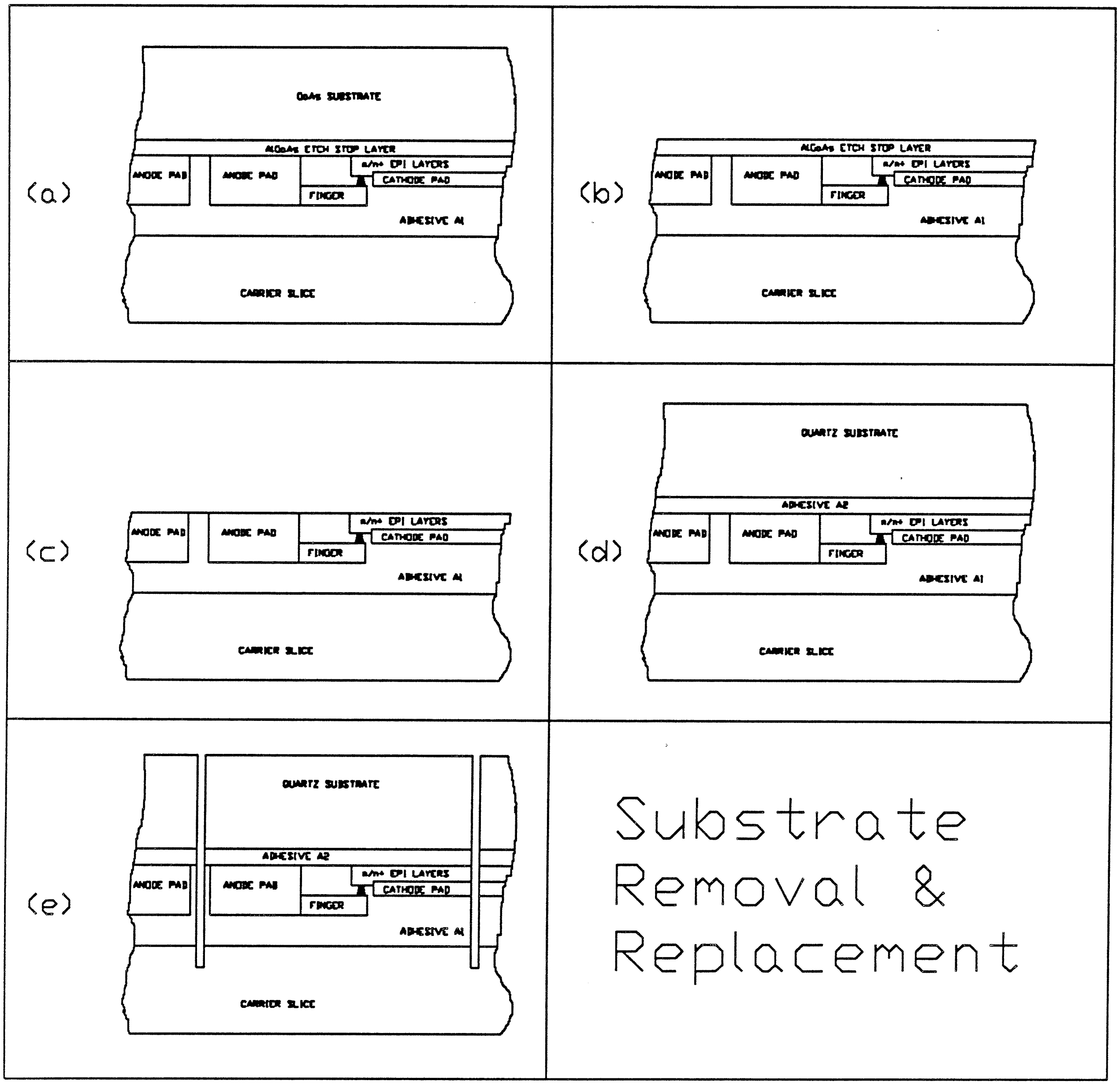

Figure 6 Basic steps in the substrate removal process: (a) bonding the diode shown in Fig. 4 to a carrier with adhesive layer, A1, (b), and (c) removal of the semiconductor substrate, (d) attachment of a 'replacement substrate' with adhesive layer, A2, (e) dicing of the wafer, and (f) (not shown) removal of individual device or circuit element chips from the carrier slice.

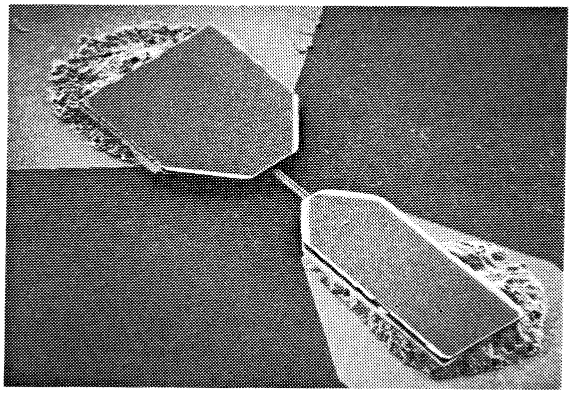

Figure 7 A 2.5 micron diameter surface-channel diode with its substrate removed mounted into a microwave circuit, on a quartz substrate.

3. InGaAs SCHOTTKY BARRIER MIXER DIODES

As was indicated in the introduction, the higher the receiver frequency the lower the available LO power. For this reason harmonic mixing, requiring LO power at half the mixer LO frequency, is commonly used. LO power needs can be further reduced by reducing the forward turn-on voltage of the Schottky diode pair. This is accomplished by reduction of the height of the Schottky barrier formed by the anode metal contact to the semiconductor. In general III-V compounds form a Schottky barrier which is very weekly dependent on the anode metal work functions. Most such electron barrier heights are very near 2/3 the electron energy gap, Eg. Thus, the Schottky barrier height can be lowered by choosing a semiconductor material with a smaller energy gap.

The ternary compound, In(x)Ga(1-x)As, offers very great promise in this application since; (a) variation of the In mole fraction, x, of the compound causes a variation in Eg and thus Schottky barrier height ϕ_B, (b) InAs, resulting from a mole fraction equal to unity, forms a Schottky barrier of negative height, critical for low resistance non-alloyed ohmic contacts, and (c) the electron mobility of the InGaAs system is generally slightly higher than that of GaAs. A plot of Schottky barrier height, ϕ_B, versus In mole fraction is given in Fig. 8. This translates nearly directly to the forward turn-on voltage of the resulting Schottky diode. With InGaAs offering such great promise we can envision a surface-channel Schottky barrier mixer diode formed on that material which is graded to InAs for the purpose of formation of a non-alloyed ohmic contact. Such a device can exhibit a forward turn-on voltage of the desired value, series resistance slightly less than that of an equivalent GaAs device, and permit formation of a non-alloyed ohmic contact having reduced specific contact resistance; a step highly desirable in nanofabrication. Investigation of the feasibility of such devices is being carried out through device modeling, and development of a compatible fabrication process.

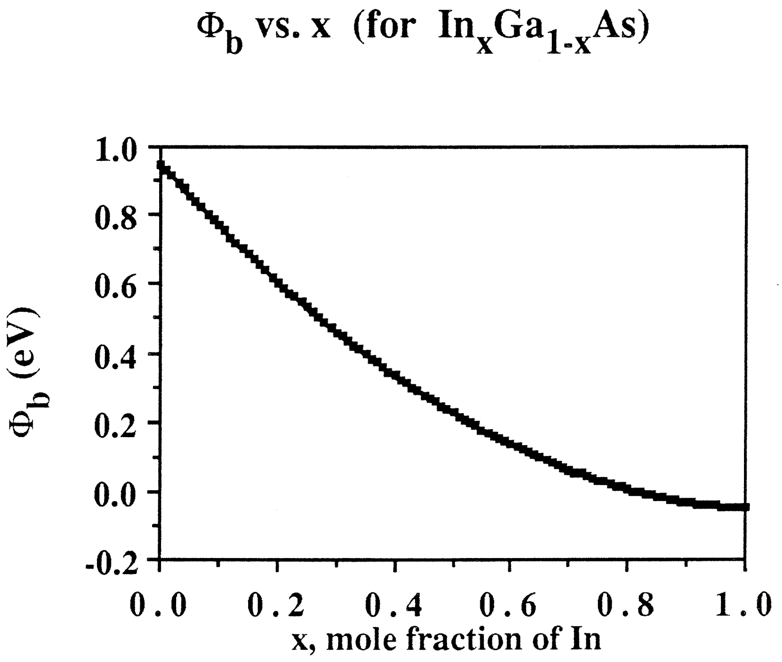

Figure 8 Predicted Schottky barrier height, ϕ_B, versus In mole fraction, x. (From Kajiyama (8))

3.1 Device Modeling. Modeling of basic device parameters such as junction capacitance, series resistance, ideality factor, and reverse breakdown voltage is quite straightforward and similar to that for GaAs diodes. Lowering of the Schottky barrier height, ϕ_B, by increasing of the In mole fraction, x, is accompanied, however, by an increase in diode reverse saturation current, Jsat. This is related to a device parameter of critical importance to mixing efficiency: the ratio of diode off-state to on-state impedance Zoff/Zon. The theoretically desirable value is infinity. Zoff is controlled by the diode parallel junction capacitance, Cj(v), and conductance, Gj(v). Since Gj(v) is directly proportional to Jsat, increasing Jsat increases device conductance. In present GaAs mixer diodes the device off-state impedance is dominated by the junction capacitive reactance. Analysis shows that too great a reduction of the device turn-on voltage through reduction of the electron barrier height can cause attendant reduction in Zoff/Zon, and thus increase mixer conversion loss. Initial indications are that an In mole fraction of .2 will not seriously degrade Zoff/Zon. This analysis is accompanied by parallel development of a compatible device fabrication technology.

3.2 Device Fabrication Technology. Major device fabrication steps are:

1. Thinning of the device active layer by anodic oxidation,
2. Feature patterning by dielectric deposition, photolithography, and etching (wet and dry),
3. Ohmic contact formation, and
4. Anode formation.

Steps 1,3, and 4 are most sensitive to change of materials. Each has been developed and characterized separately. None exhibited great deviation from the equivalent step used in GaAs diode fabrication. A test batch of InGaAs devices was fabricated from material having non-ideal electrical parameters. All processing proceeded as expected and the resulting diode current-voltage characteristics were quite encouraging in that they exhibited device parameters expected for that material.

4. SUPERCONDUCTIVE MIXER ELEMENTS

The SIS quasiparticle tunnel junction mixer is very attractive due to its extremely low shot noise, potential for conversion gain, and low LO power requirement. In the last few years SIS mixers have been established as having the highest sensitivity at millimeter wavelengths, with mixer noise temperatures comparable to the photon noise temperature, 5 K at 100 GHz.(9). Detailed theoretical analysis, however, has shown that an optimized SIS receiver should be capable of near quantum-limited performance to nearly twice the gap frequency; typically on the order of 1-2 THz. (10) Thus, the goal of this facet of our research to carry out work necessary to yield excellent mixer elements for application from 100 GHz to 1 THz for radio astronomy and associated applications. Fabrication processes are being developed for two types of junctions which are attractive for this application: Nb/Al-Al_2O_3/ Nb trilayer devices, and NbCN edge structures. The results of this research are presented in the following sections.

4.1 Trilayer Junction Fabrication. Nb/Al-Al_2O_3/Nb trilayer SIS junctions are physically robust and exhibit stable electrical characteristics with time and thermal cycling between 4.2 and 300 K. Integral to the fabrication process is the formation of a 'trilayer' film composed of a thin (20 Å) layer of insulating Al_2O_3 sandwiched between two thicker layers of Nb, all deposited in a system during one vacuum cycle. The deposition system used is modelled after that of Huggins and Gurvitch (11) but achieves a base pressure of 5 x 10^-10 Torr. A sputtering pressure of 14 mTorr is utilized to obtain stress-free Nb films. Intrinsic stress existing in the electrode films has been found to be detrimental to SIS junction quality (12).

Junction areas can be simply defined by anodization of the upper Nb film, however the resulting junctions are not acceptable for millimeter wave application due to the relatively high dielectric constant of Nb_2O_5 which gives an unacceptably high shunt capacitance. It is also highly desirable for the junctions to have individual tuning elements for optimum performance. A common alternative to the utilization of anodization is a technique by which a lift-off resist feature is machine aligned to be positioned inside the perimeter of a previously defined junction area. The subsequently deposited insulation layer covers the critical perimeter of the junction. The main disadvantage of this and other machine-aligned techniques is the alignment difficulty experienced for devices having feature sizes smaller than three microns.

We have chosen to develop a trilevel resist self-aligned technique which is depicted in Fig. 9.

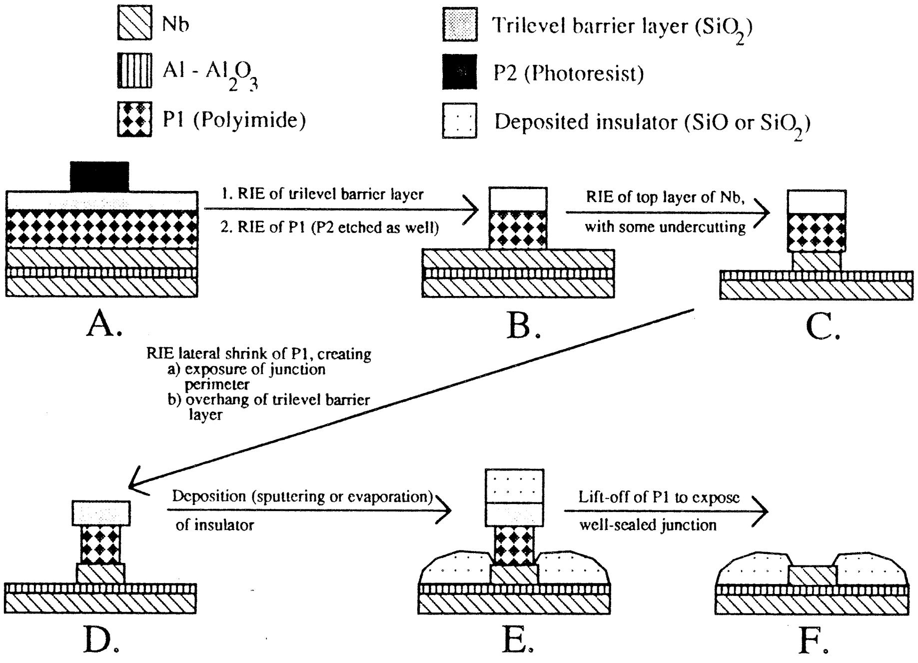

Figure 9 Trilevel resist self-aligned process.

In this process the patterned Nb/Al-Al_2O_3/Nb trilayer film is covered with a planarization layer upon which a thin layer of SiO_2 is deposited. This composite layer is then photolithographically patterned and etched in a two step reactive ion etching process. After definition of the junction area by reactive ion etching, RIE, we reduced the lateral dimension of the planarization layer, revealing the perimeter of the junction area and simultaneously forming an excellent liftoff stencil shown in Fig. 10. The subsequently deposited insulation layer actually overlaps the top Nb electrode and seal the junction. A portion of a wafer showing this insulation layer and associated tuning element electrodes in a six junction array is given in Fig. 11.

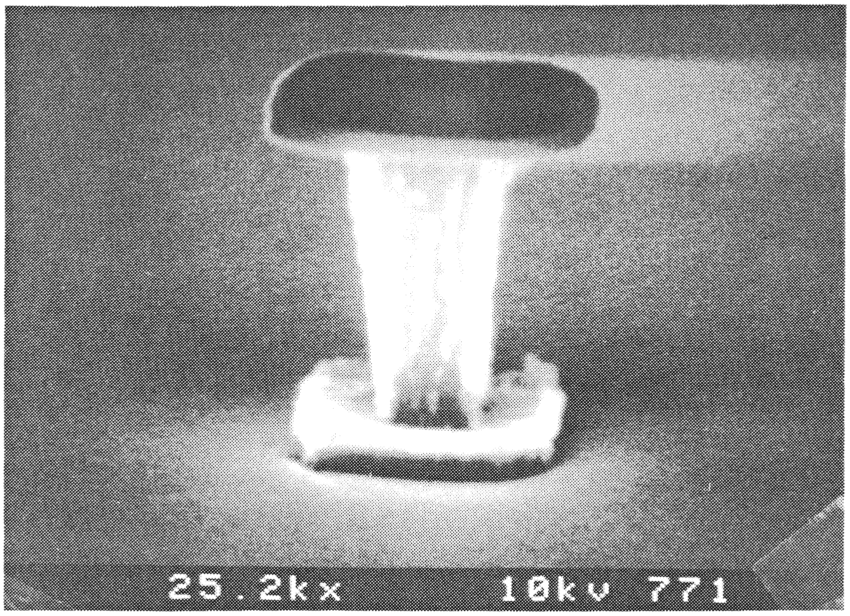

Figure 10 SEM photograph of trilevel resist overhang.

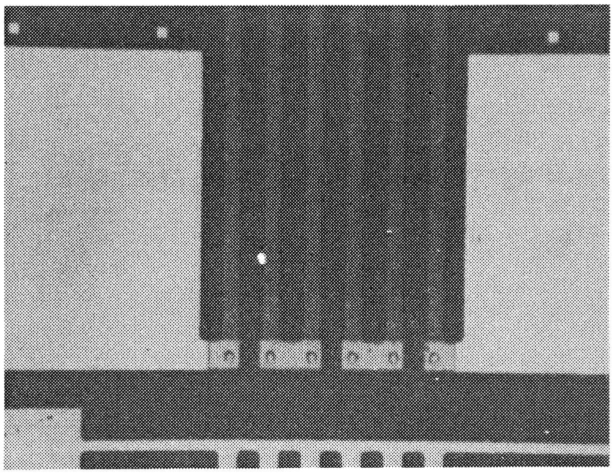

Figure 11 A micrograph of a six junction array with the overlapping SiO insulating layer in place. Also shown are the tuning element electrodes.

4.2 Trilayer Device Electrical Performance. The most striking feature of SIS junctions produced in our lab by this process is their low leakage current, a property critical to mixer elements. Figure 12 shows the I-V characteristics of a three element series array of 1.5 x 1.5 micron junctions exhibiting critical current density of 1400 A/cm^2.

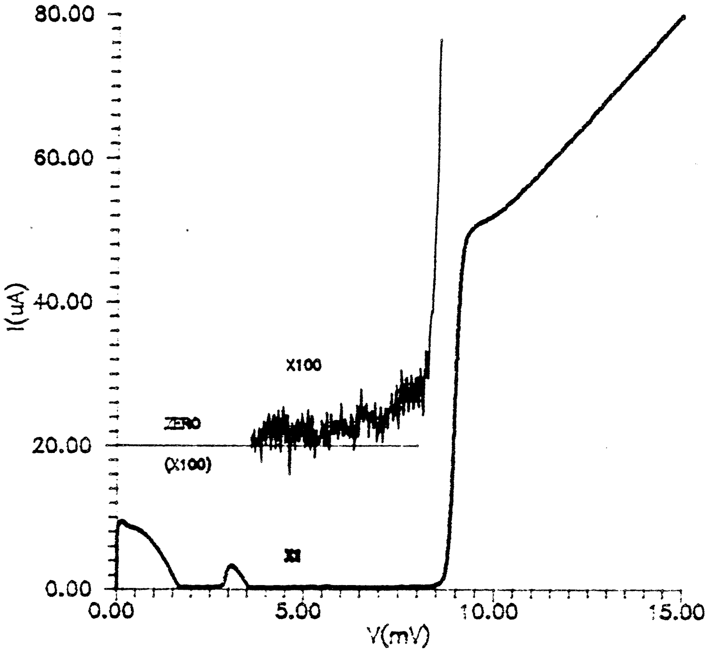

Figure 12 Current-voltage characteristics of a series array of three 1.5x1.5 micron Nb/Al_2O_3/Nb junctions.

As can be seen, each junction has a turn-on voltage of 2.93 mV, a gap width of 100 microvolts, and a very weak 'knee'. This extremely low leakage current is clearly less than 0.1% of the quasiparticle current rise, and corresponds to a quality parameter, Vm, value greater than 1.5 V. This leakage current is considerably less than that reported for any small SIS junction made from any superconductor material to date.

Work is presently proceeding toward improving the reliability of this fabrication technique. The primary difficulty encountered involves repeatability and uniformity in lateral etching of the planarization layer which provides the lift-off stencil. Various planarization materials and chemical treatments are being examined.

4.3 NbCN/Si:H/NbCN Edge Junctions. NbCN possesses one of the largest superconducting energy gaps, 2.6 mV. Since twice the gap frequency is roughly the upper limit for near quantum-limited receiver sensitivity, NbCN is very attractive for high frequency applications. Our work in this area has centered on developing an edge junction process since it provides a very straightforward method of fabricating small area junctions required for submillimeter wave use. Most of this work has focussed on NbCN/Ox/PbBi edge junctions. Such devices resulting from our work have exhibit the highest quality factor, Vm(3mV), values, >100 mV at 4.2 K, of any edge junctions of which we are aware (13). An all-NbCN edge junction would, however, be more desirable than our present PbBi counterelectrode structure due to its refractory nature. We are presently developing a NbCN/Si:H/NbCN edge junction fabrication process in collaboration with E. J. Cukauskas of the Naval Research Laboratory. A pictorial drawing of this structure is shown in Fig. 13.

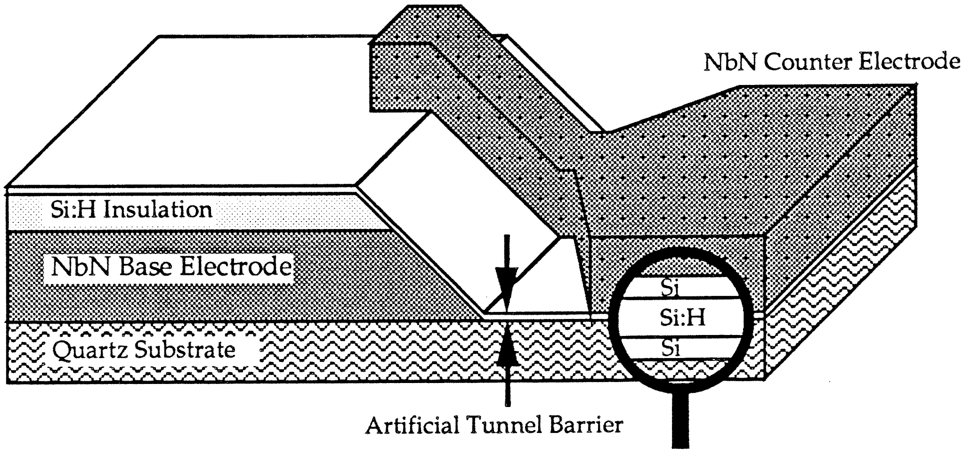

Figure 13 Pictorial drawing of NbCN/Si:H/NbCN edge junction.

The hydrogenated Si barrier, which is deposited at 700 K, has a specific capacitance approximately two times smaller than that obtained in using MgO, which is the typical barrier employed in the NbCN system. The Si barrier technology, therefore, has the advantage of permitting deposition of a superior 'hot' NbCN counterelectrode and the use of junction areas which are twice those of equivalent devices employing MgO as the barrier material. The research on this structure has focused primarily on the barrier deposition and counterelectrode RIE steps. Completion of the first set of devices is anticipated in the near future.

5. SUMMARY

Presented in the above sections are the primary needs perceived for mixer elements of highest sensitivity heterodyne receivers operating at frequencies in excess of 100 GHz, along with research efforts oriented at direct fulfillment of those needs. The mixer element of choice depends on the mixer operating temperature.

In the case of semiconducting mixer elements it was pointed out that a Schottky diode having excellent mechanical stability (devoid of a whisker contact), and easily formed in conjunction with other diodes or in circuits is essential. Presented in answer to this need is the surface-channel diode having record low shunt capacitance. Also presented is the new substrate removal technology which permits near MMIC performance with the flexibility of hybrid technology. The need for reduced LO power will be met by use of mixer elements having a lower turn-on voltage. The InGaAs technology yields great promise in this area and will permit formation of non-alloyed ohmic contacts having reduced specific contact resistance. This material-device system is being investigated.

In the case of superconductive mixer elements the need for mechanical stability and robustness in temperature cycling is answered by refractory materials. The Nb trilayer technology meets this need quite well. In addition, need for materials having potential for operation in the THz region is answered by the NbN system.

While the above mentioned are perceived needs which will, most certainly, be joined by others, unforseen at this time; it is felt that the presented technologies and suggested study areas will answer the presently perceived needs of heterodyne receiver elements for operation above 100 GHz in the near future.

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