points due to the inherent sensitivity limitations of his instrument system.

Recently, McAvoy and Buckmaster [15]–[18] have developed a new 9-GHz instrumentation system to measure the complex permittivity of high-loss liquids which introduces refinements that permit ϵ' and ϵ'' to be determined to ~ 0.05 percent and ~ 0.5 percent, respectively. This is a significant advance in precision since it represents an improvement by factors of sixteen and seven, respectively [15],[16]. It is unfortunate that Zanforlin [1] failed to provide an experimental evaluation of the errors in his instrumentation system since it is a useful contribution to the methodology of complex permittivity measurements. It is concluded that the multimode nonresonant reflection cell is a useful approach, particularly at millimeter wavelengths, where the single-mode nonresonant transmission cell is difficult to realize. However, the measurement accuracy is limited to ~ 1 percent due to limitations in the data fitting procedure.

References

[1] L. Zanforlin, "Permittivity measurements of lossy liquids at millimeter-wave frequencies," *IEEE Trans Microwave Theory Tech.*, vol MTT-31, pp. 417–419, May 1983.

[2] K. Hallenga, "New method for very sensitive dielectric difference measurements on high-loss liquids at microwave frequencies," *Rev. Sci. Instrum.*, vol. 46, pp. 1691–1696, Dec 1975.

[3] R. Van Loon and R. Finsy, "The precise microwave permittivity measurement of liquids using a multipoint technique and curve-fitting procedure," *J. Phys. D. Appl. Phys.*, vol 8, pp. 1232–1243, July 1975.

[4] M. W. P. Strandberg, "EMR notes from Strand labs," Strand Labs Inc, pp. 1–9, Apr. 1964.

[5] R. J. King, *Microwave Homodyne Systems.* Stevenage, Herts, England: Peter Peregrinus Ltd., 1978.

[6] H. A. Buckmaster and J. C. Dering, "Experimental sensitivity study of a 9 GHz electron paramagnetic resonance spectrometer," *Can. J. Phys.*, vol. 43, pp. 1088–1098, June 1965.

[7] H. A. Buckmaster and J. C. Dering, "The application of phase-lock microwave frequency stabilizers to electron paramagnetic resonance spectrometers," *J. Scientific Instrum.*, vol. 43, pp. 554–557, Aug. 1966.

[8] H. A. Buckmaster and J. C. Dering, "The fundamental limit to the balance of a microwave bridge containing a dispersive element," *IEEE Trans. Instrum. Meas.*, vol. IM-16, pp. 13–18, Mar. 1967.

[9] H. A. Buckmaster and J. C. Dering, "Limiting sensitivity of EPR spectrometers at high power levels," in *Proc. of the XIV Colloque Ampere* (Ljubljana), Sept. 6–11, 1966, R. Blinc, Ed. Amsterdam: North Holland, 1967, pp. 1017–1022.

[10] H. A. Buckmaster and J. C. Dering, "A 9 GHz, single-klystron, EPR spectrometer using superheterodyne demodulation," *Can J. Phys.*, vol. 45, 107–117, Jan. 1967.

[11] J. C. Dering, "Sensitivity considerations in electron paramagnetic resonance spectrometers," M.Sc. thesis, Physics Dept., Univ. of Alberta at Calgary, unpublished, 1964.

[12] J. C. Dering, "Theoretical and instrumental studies in electron paramegnetic resonance I. An investigation of the design of high-sensitivity and stability EPR spectrometer and a survey of the theory and application of generalized spin-Hamiltonian," Ph.D. thesis, Physics Dept., Univ. of Calgary, unpublished, 1967.

[13] M. W. P. Strandberg, "Sensitivity of radio frequency measurements in the presence of oscillator noise," *Rev. Sci. Instrum.*, vol. 43, pp. 307–316, Feb. 1972.

[14] For example, MA-40090 10 GHz zero IF Schottky mixer diode.

[15] J. G. McAvoy, "Two cell microwave complex permittivity measurement system," M.Sc. thesis, Physics Dept., Univ. of Calgary, unpublished, 1983.

[16] J. G. McAvoy and H. A. Buckmaster, "The 9 GHz complex permittivity of water at 293 K and 298 K," *J. Phys. D.: Appl. Phys.*, vol. 16, pp. 2519–2523, Dec. 1983.

[17] J. G. McAvoy and H. A. Buckmaster, "The 9 GHz complex permittivity of 0.001–0.05 M KCl in water at 293 K," *J. Phys. D.: Appl. Phys.*, vol. 17, pp. 2081–2085, Nov. 1984.

[18] J. G. McAvoy and H. A. Buckmaster, "A dual channel instrumentation system for precision, differential microwave complex permittivity measurements," *J. Phys. E. Sci. Instrum.*, vol. 18, pp. 244–250, Mar. 1985.

[19] H. Zaghloul and H. A. Buckmaster, "The complex permittivity of water at 9.356 GHz from 10°C to 40°C," *J. Phys. D.: Appl. Phys.*, vol. 18, 1985.

1.5-GHz GaAs Surface Acoustic Wave Delay Lines

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Abstract **—Surface acoustic wave (SAW) delay lines fabricated on commercially available (100) cut GaAs have been used to control oscillators at frequencies as high as 1.5 GHz. These high frequencies were obtained by operating at the second overtone of transducers with three electrodes per wavelength. A theoretical and experimental study of the temperature coefficient of frequency of SAW oscillators on GaAs was performed. Tables display the GaAs elastic constants and their temperature coefficients, as well as the experimental and theoretical surface acoustic wave propagation characteristics of selected GaAs orientations.**

I. Introduction

Surface acoustic wave (SAW) delay lines fabricated on gallium arsenide have been used to control oscillators at frequencies up to 1.5 GHz. The oscillators are being developed to meet the need for stable sources on gallium arsenide monolithic microwave integrated circuits. If an oscillator is to be included on a monolithic chip, it must meet several requirements. It must be physically small; it must be compatible with the fabrication process used for the electronic circuit; its output frequency must be high to minimize the need for power-hungry multiplier chains with their associated high noise floor; it must have a useful degree of stability. These 1.5-GHz devices, the highest frequency GaAs SAW-controlled oscillators reported to date, suggest that surface acoustic wave devices can meet the requirements of MMIC applications.

II. Fabrication

Since gallium arsenide is piezoelectric as well as semiconducting, fabrication of gallium arsenide SAW devices is straightforward. Our 1.5-GHz delay lines were fabricated from commercially available polished GaAs wafers. These (100) cut wafers were semi-insulating with no intentional doping. This is the type of wafer which would typically be used for ion-implanted GaAs electronics. On the (100) GaAs surface, the surface acoustic waves propagate along the [110] direction with a velocity of 2860 M/s, an electromechanical coupling ($2\Delta V/V$) of 6.4×10^{-4}, and a zero power flow angle.

Rectangular substrates are easily cleaved from the (100) cut wafers along perpendicular {110} planes. The cleavage planes provide an excellent reference for SAW transducer alignment. "Three-Halves" (3/2) electrode interdigital transducers [1] operating at the second overtone were selected for the delay lines. The 3/2 electrode transducer employs three interdigital electrodes per wavelength at the fundamental frequency. Each electrode is 1/6 of a wavelength wide with a 1/6 wavelength space. Like the double electrode (four electrodes per wavelength, each 1/8 of a wavelength wide), it overcomes the problem of mechanical reflections in the transducer passband. At the fundamental frequency, the wider 3/2 electrodes ease the fabrication tolerances relative to the double electrode. Each transducer consists of 173 electrodes with 0.62-μm lines and spaces and an acoustic aperture of 350 μm. The transducers were photolithographically defined using the lift-off technique and a 10× direct step on the wafer exposure system [2]. Center-to-center transducer separation was 3

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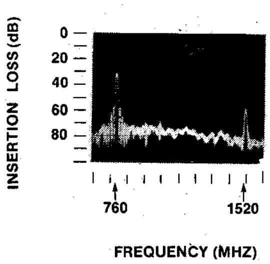

Fig. 1. Insertion loss versus frequency for (100) cut, [110] propagating GaAs delay line (vertical = 10 dB/div, horizontal = 100 MHz/div).

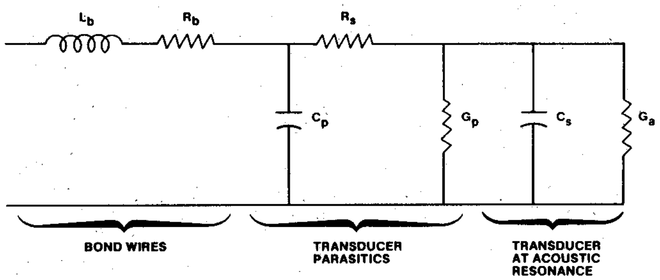

Fig. 2. Model for estimating the insertion loss of GaAs SAW delay line.

mm. Transducer metalization was 60 Å Cr, 600 Å Al. The metal forms a Schottky contact to the GaAs, so the interdigital structure behaves like back-to-back diodes. Curve tracer measurements reveal a reverse bias leakage resistance of approximately 18 KΩ which shunts the acoustic radiation resistance. The effect of this resistance on acoustic performance is negligible. The interdigital structure breaks down at approximately ±5.5 V (60 Hz), corresponding to an average electric field of 9×10^6 V/m between electrodes. At typical oscillator drive levels of 0 dBm, the transducer will not approach these breakdown field levels.

III. Experiment

Since the delay lines were fabricated primarily for temperature coefficient measurements, they were not optimized for low loss, and no external reactive tuning was used. A sweep of the delay-line transmission versus frequency shown in Fig. 1 reveals an insertion loss of 33 dB for the fundamental response at 0.76 GHz and 55 dB at the 1520-MHz overtone. Bidirectional loss accounts for 6 dB, while acoustic propagation loss over the 3 mm path contributes ~10 dB at 1.52 GHz. Analysis of the transducer electrical port reflection coefficient provides estimates of other loss contributions. The analysis was performed by fitting the model of Fig. 2 to experimental data using the Super Compact® CAD program. The bond wires contribute ~3 Ω of parasitic resistance and 9-nH stray inductance. Transducer metalization adds ~5 Ω of series resistance. The static capacitance of the transducer is ~3.2 pF. There is an additional stray capacitance of 0.3 pF contributed primarily by bonding pads. The capacitance resonates with the bond wires near 900 MHz. Therefore, in a 50-Ω system, the transducer presents a capacitive load at the fundamental and an inductive load at the overtone. Decreasing the inductance to ~3 nH would tune out the reactance at the overtone, reducing the insertion loss by ~6 dB. At the 0.76-GHz acoustic resonance, the estimated transducer radiation conductance is 770 μS, while at the 1.52 GHz overtone, the conductance is ~1540 μS. Because of a defect in the photomask, the radiation conductance is shunted by a 3300-μS parasitic conductance. In a monolithic implementation of the delay line, the parasitics could be substantially reduced. Elimination of the parasitic shunt conductance and halving the series resistance would lead to an additional 7-dB reduction of insertion loss. With these improvements and optimization of the acoustic radiation conductance, an insertion loss of ~30 dB at 1.5 GHz can be expected.

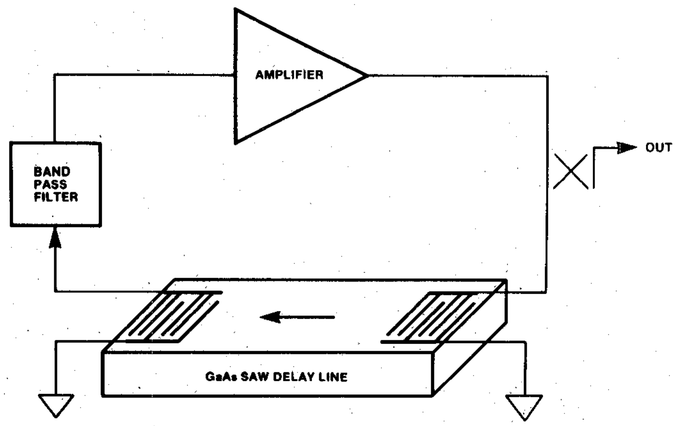

Fig. 3. SAW delay-line feedback oscillator configuration.

We formed an oscillator by placing the delay line in an amplifier feedback loop, using a bandpass filter to select either the upper passband or the lower passband as shown in Fig. 3. Although the phase-noise performance of the oscillators has not been measured, the noise characteristics can be inferred from the insertion loss and the Q of the delay line [3]. The Q determines the noise intercept frequency $F_n = F_o/2\ Q$, where F_o is the oscillator frequency. For offsets just less than ω_n, the phase noise begins to rise from the noise floor at a rate of 20 dB/decade. (For even smaller offsets, the phase noise rises faster than 20 dB/decade.) At offset frequencies greater than ω_n, the phase noise is frequency independent at the noise-floor level. An effective Q of ~5100 for our 1.5-GHz delay line can be estimated from the relationship $Q_{\text{eff}} = \omega_o\tau/2$, where ω_o is the oscillator radian frequency and τ the measured group delay [4]. This value is similar to the Q's reported for quartz SAW delay lines in this frequency range [4], and yields a noise intercept frequency of ~150 KHz. At L-band frequencies, SAW oscillators typically have a lower noise floor than oscillator–multiplier chains. This is because frequency multiplication by a factor N raises the noise floor by a factor N^2 [3]. However, the noise floor also rises in direct proportion to the delay-line insertion loss. Therefore, to achieve the expected noise-floor advantage, the insertion loss must be reduced as discussed above.

One further improvement in this oscillator structure could be made by using a technique described by Kerbel [5]. He showed that two dissimilar transducers operating at the same frequency but at different overtones can eliminate the need for bandpass filters. In fact, a double-electrode third overtone transducer operating at 1.5 GHz would have approximately the same linewidth requirement as the 3/2 transducer. For 3/2 electrodes operating at the 1.5-GHz second overtone, the line width is $2\times\lambda/6 = 0.33$, $\lambda = 0.62$ μm, while double electrodes at the third overtone require linewidths of $3\times\lambda/8 = 0.375$, $\lambda = 0.706$ μm.

IV. Temperature Coefficients

Experiments were performed to measure the temperature coefficient of frequency of the oscillators. Under computer control, the delay line came to equilibrium at each temperature before the frequency reading was made. The delay line was considered to be at equilibrium when the temperature of its machined aluminum package, measured at one half second intervals by an HP 2804A quartz thermometer, changed by less than 5 millidegrees in 5 min.

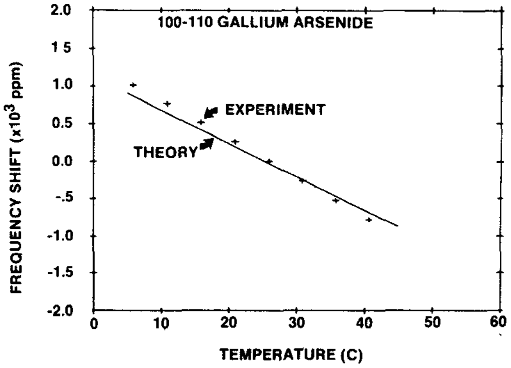

Fig. 4. GaAs SAW delay-line oscillator frequency as a function of temperature. Experimental points are shown with the computed solid curve.

TABLE I
ELASTIC STIFFNESS CONSTANTS AND THEIR TEMPERATURE COEFFICIENTS BASED ON A FIT TO DATA IN [7]

ij	$C_{ij}(25)$ ($\times 10^{11}$ N/m^2)	$TC^{(1)}_{ij}$ ($\times 10^{-4}$/°C)	$TC^{(2)}_{ij}$ ($\times 10^{-7}$/°C^2)	$TC^{(3)}_{ij}$ ($\times 10^{-9}$/°C^3)
11	1.18404	-1.0197	0.13622	0.69266
12	0.53733	-1.29207	-1.4983	1.4848
44	0.59107	-0.98098	0.64093	0.86992

$C_{ij}(T) = C_{ij}\,[1 + TC^{(1)}_{ij}(T-25) + TC^{(2)}_{ij}(T-25)^2 + TC^{(3)}_{ij}(T-25)^3]$

$C_{ij}(T)$ = Elastic Stiffness Constant at Temperature T

$TC^{(n)}_{ij}$ = nth Order Temperature Coefficient of C_{ij} Evaluated at 25C.

TABLE II
SURFACE ACOUSTIC WAVE PROPAGATION CHARACTERISTICS ON SELECTED CUTS OF GALLIUM ARSENIDE

Euler Angles	Temperature Coefficient of Frequency (PPM)		Electro-Mechnical Coupling $2\,\Delta V/V$ ($\times 10^{-4}$)	SAW Velocity (m/sec)		Power Flow Angle (Deg)	Comment
	Theory	Exp		Theory	Exp		
45, 0, 0	-46.2	-52.0	6.4	2856	2841	0	100 Cut, 110 Prop
45, 54.74, 30	-44.1	-50.7	2.0	2596	2598	0	$1\bar{1}1$ Cut, 121 Prop
45, 54.74, 0	-34.8	--	+ 0	2421	--	0	$1\bar{1}1$ Cut, 110 Prop
45, 35.264, 90	-44.2	-50.8	2.88	2611	2621	0	$2\bar{1}1$ Cut, 111 Prop
45, 90, 90	-45.8	-50.2	1.80	2812	2804	0	$1\bar{1}0$ Cut, 001 Prop
45, 90, 0	-35.5	--	+ 0	2392	--	0	$1\bar{1}0$ Cut, 110 Prop
15, 30, 60	-38.9	--	3.06	2609	--	2.4	Moderate TCF and Coupling

The experimental temperature sensitivity of the oscillator frequency is shown as the plotted points in Fig. 4. A least-squares line through these points would have a slope of -52 ppm/°C.

In an effort to achieve lower temperature sensitivity, we performed an experimental and theoretical investigation of the temperature dependence of SAW propagation on GaAs. The temperature coefficient of frequency (TCF), electromechanical coupling, SAW velocity, and power flow angle were computed for various crystallographic orientations [6]. The calculations were performed for a systematic sampling of all unique plate orientations and propagation directions. The sample was designed to identify crystallographic orientations having both a high piezoelectric coupling to the SAW mode and a low temperature coefficient of delay. To perform these calculations, we obtained the elastic constants and their temperature coefficients by digitization and least-squares analysis of the data plotted by Cottam and Saunders [7]. The constants and coefficients are listed in Table I for a fit valid over the temperature range of -50°C to $+50$°C. Table II lists the computed SAW properties for a representative selection of orientation along with some experimental results. SAW velocities were experimentally determined from the mode spacing in multimode oscillators while the TCF was measured for delay-line oscillators in the computer-controlled environmental chamber over a temperature range of -10°C to 50°C. The computed temperature sensitivity for (100) cut, [110] propagation is also plotted in Fig. 4. The computed TCF ranged from a high of 46.2 ppm to a low of 34.8 ppm. Electromechanical coupling ranged from a high of 6.4×10^{-4} to zero. Unfortunately, those orientations with the lowest TCF also have low or zero coupling to the SAW mode. A modest tradeoff of temperature coefficient for coupling can be made for some orientations, notably the one with Euler angles 15, 30, 60. Agreement between theory and experiment is within one percent for SAW velocities, but the computed TCF's are consistently lower than the experimental TCF. This discrepancy may be due to the improvement in the quality of gallium arsenide crystals since the Cottam and Saunders measurements were published in 1973.

V. CONCLUSIONS

We have shown that GaAs SAW delay lines can be useful for stabilizing monolithic oscillators at frequencies up to 1.5 GHz. Our computations of SAW propagation characteristics generally indicate that the orientations with low TCF also have low coupling. Given the results of this study and the fact that the semiconductor industry is committed to the (100) cut, we conclude that the (100) cut, [110] propagating orientation is preferred for GaAs SAW applications. If temperature compensation is required, it must be accomplished by other means such as thin-film overlays [8] or digital compensation [9].

Acknowledgment

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References

[1] A. J. Slobodnik, Jr., J. H. Silva, and G. A. Roberts, "SAW filters at 1 GHz fabricated by direct step on the wafer," *IEEE Trans. Sonics Ultrason.*, vol. SU-28, pp. 105–106, Mar. 1981.
[2] J. H. Silva, A. J. Slobodnik, Jr., and W. J. Kearns, "A 2.2 GHz SAW delay line fabricated by direct optical projection," *IEEE Trans. Sonics Ultrason.*, vol. SU-26, pp. 312–313, July 1979.
[3] D. B. Leeson, "A simple model of feedback oscillator noise spectrum," *Proc. IEEE*, vol. 54, pp. 329–330, Feb. 1966.
[4] G. K. Montress, R. A. Wagner, and M. Gilden, "Stable microwave SAW oscillators for aging studies," in *1979 Ultrasonics Symp. Proc.*, IEEE Cat. No. 79CH1482-9, pp. 886–890.
[5] S. J. Kerbel, "Design of harmonic surface acoustic wave oscillators without external filtering and new data on the temperature coefficient of quartz," in *1974 Ultrasonics Symp. Proc.*, IEEE Cat. No. 79CH1482-9, pp. 276–281.
[6] R. T. Webster, "Temperature coefficients of surface acoustic wave delay on GaAs," in *1981 Ultrasonics Symp. Proc.*, IEEE Cat. No. 81CH1689-9, pp. 360–363.
[7] R. I. Cottam and G. A. Saunders, "The elastic constants of GaAs from 2 K to 320 K," *J. Phys. C, Sol. State Phys.*, vol. 6, no. 13, pp. 2105–2118, July 9, 1973.
[8] T. W. Grudkowski and M. Gilden, "Realization of temperature-compensated GaAs surface acoustic wave delay lines," *Appl. Phys. Lett.*, vol. 38, no. 6, pp. 412–413, Mar. 1981.
[9] A. J. Slobodnik, Jr., R. D. Colvin, G. A. Roberts, and J. H. Silva, "A digitally compensated SAW oscillator," in *1981 Ultrasonics Symp. Proc.*, IEEE Cat. No. 81CH1689-9, pp. 135–138.

Planar Millimeter-Wave Diode Mixer

N. J. CRONIN AND V. J. LAW

***Abstract*—A new mixer has been built, using a planar GaAs Schottky-barrier diode, for operation at frequencies around 100 GHz. The mixer has low noise temperature and conversion loss and low local oscillator power requirement. The design is such that construction of scaled versions should be possible for operation up to 200 GHz.**

I. Introduction

For frequencies above 100 GHz, most high-performance mixers still utilize whisker-contacted Schottky-barrier diodes [1]. Satellite borne applications in the short millimeter region are of increasing importance, and there is thus a growing demand for systems capable of withstanding the rigors of space flight. Whisker-contacted diodes have been used in space [2] but more rugged and reliable mixers are being sought. Excellent beam-lead diodes have been developed in a number of laboratories around the world [3],

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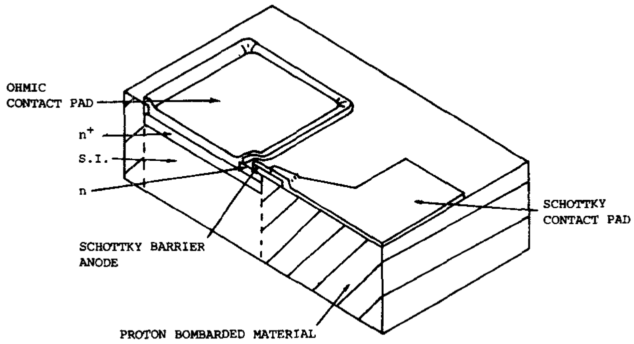

Fig. 1. Planar GaAs Schottky-barrier diode.

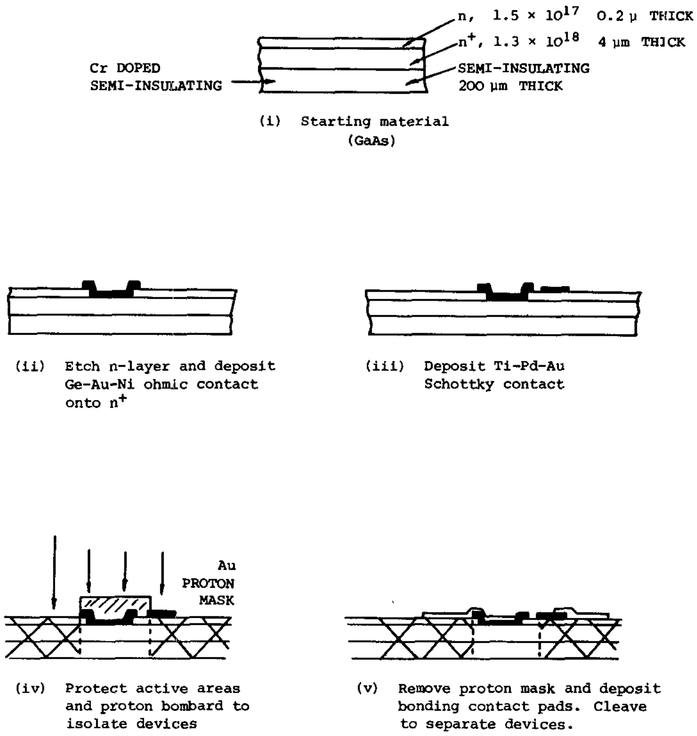

Fig. 2. Schematic representation of the planar diode process.

[4] but parasitics associated with the contact leads have limited their use to around and below 100 GHz. There is a need, therefore, to develop new mixers which combine the ruggedness of the beam-lead structures with the high-frequency capability of whiskered devices [5].

We report a new mixer, operating in the band 90 to 110 GHz. The design utilizes a custom-built, planar, GaAs Schottky-barrier diode soldered directly into a suspended-substrate stripline circuit without the use of bonding leads. This configuration exhibits low parasitics and should not be subject to the frequency limitations of conventional beam-lead designs.

II. The Diode

Fig. 1 is a sketch of the overall configuration of the planar diodes used. The devices were fabricated by a process which is summarized in Fig. 2. Two different types of diode have been assessed. Type-A were fabricated by the authors at the Plessey, Allen Clark Research Centre, Towcester, England; type-B were kindly loaned to us by Dr. B. J. Clifton of M.I.T. Lincoln Laboratories, MA. Fig. 3 shows the dimensions of the type-A