Low-Parasitic, Planar Schottky Diodes for Millimeter-Wave Integrated Circuits

JOHN W. ARCHER, SENIOR MEMBER, IEEE, ROBERT A. BATCHELOR, AND C. J. SMITH

Abstract —**The design and fabrication of air-bridged, ultra-low-capacitance Schottky barrier diodes are described. Mott diodes, for mixer applications, and varactor diodes, for use in frequency multipliers, have been produced simultaneously on epitaxial wafers grown by molecular beam expitaxy. Typical mixer diodes have a nominal anode contact area of 4μm², exhibit a total zero-bias capacitance of 4.0–4.5 fF (including a parasitic capacitance of approximately 1.0 fF) and a series resistance of 6–8 Ω. Diode chips have been incorporated in hybrid integrated circuit (MIC) mixers for 33–50 GHz and 75–110 GHz and an MIC frequency tripler for 90–140 GHz. Fully monolithic (MMIC) subharmonically pumped mixers for 75–110 GHz have also been fabricated and tested.**

I. Introduction

IN RECENT YEARS, the growth of millimeter-wave technology has received significant impetus from applications in military radar, communications, and passive imaging [1]. Requirements for millimeter-wave equipment in commercial systems are also expected to increase [2]. The size, cost, and reliability of traditional, waveguide-mounted devices and components have been shown to be inadequate for these applications. A more viable approach —millimeter-wave hybrid integrated circuit technology (MIC)—which utilizes several discrete semiconductor devices on a subsidiary dielectric substrate, has been developed to maturity in recent years. An international effort is now under way to develop high-performance monolithic GaAs integrated circuits (MMIC's) [3] to replace the hybrid IC's currently available, thereby reducing unit costs and enhancing performance and reliability. As a consequence, a substantial growth in the use of millimeter-wave systems has been predicted [1], [2].

Research at the CSIRO Division of Radiophysics is aimed at developing monolithic millimeter-wave integrated circuits for applications in low-noise receivers. In particular, this paper describes the design and fabrication of a range of high-performance, planar, air-bridge-connected Schottky barrier diodes which are suitable for monolithic integration in millimeter-wave mixer and frequency multiplier circuits. The diode fabrication process is outlined and the performance of discrete devices is detailed. The performance of MIC and MMIC mixers and multipliers is presented.

Manuscript received February 13, 1989; revised July 31, 1989.
The authors are with the Division of Radiophysics, CSIRO, P. O. Box 76, Epping, N.S.W. 2121, Australia.
IEEE Log Number 8931554.

II. Diode Fabrication

For successful monolithic integration of Schottky diodes, the fabrication process must meet a number of requirements. The diodes must be electrically isolated from one another and from passive circuit elements, except where interconnections are specifically required. The interconnections between diode and circuit must not introduce significant parasitic resistance, inductance, or capacitance. In addition, passive transmission line structures must be fabricated on a high-quality dielectric substrate in order to minimize circuit losses.

The CSIRO design concept is shown in Fig. 1. The diodes are formed on an epitaxial structure which is grown on a semi-insulating, undoped GaAs wafer. The substrate material provides a low-loss dielectric to support the passive elements of the circuit. The design specification for the epitaxial layers, grown by molecular beam epitaxy, consists of 2.0 μm of low-resistivity GaAs doped at 2×10^{18} cm^{-3}, topped with a 1 μm GaAs active layer with doping 5×10^{16} cm^{-3}. The 1-μm-thick active layer allows the fabrication of varactor diodes.

Since ohmic contact alloying has a limited depth range, the active layer must be thinned or removed before forming contacts to the low-resistivity GaAs. Furthermore, for Mott diodes, which are fully depleted at zero bias, the active layer must be thinned to a thickness of 0.15 μm. These considerations dictate the use of a two-stage mesa etching process. Firstly, a resist stencil defining mesas for the formation of varactor diodes is formed on the active layer, using conventional photolithography (as used throughout the fabrication process). The remaining epitaxial material is thinned to 0.15 μm by a controlled isotropic etching process. Secondary mesas are then defined where ohmic contacts and mixer diodes are to be formed and the remaining active layer is etched away to a depth of 3 μm, leaving the semi-insulating substrate exposed.

The Au/Ge/Ni ring cathode contact for all diodes is formed using conventional lift-off processing and alloying through the active layer to the n^+ layer. The Schottky barrier metal, a thermally evaporated Ti/Pt/Au trilayer, is deposited next. It is also used for interconnections and as the circuit metal for stripline structures, forming the base for subsequent up-plating.

Surface oriented diodes require connection between the anode contact and the external circuit, analogous to the

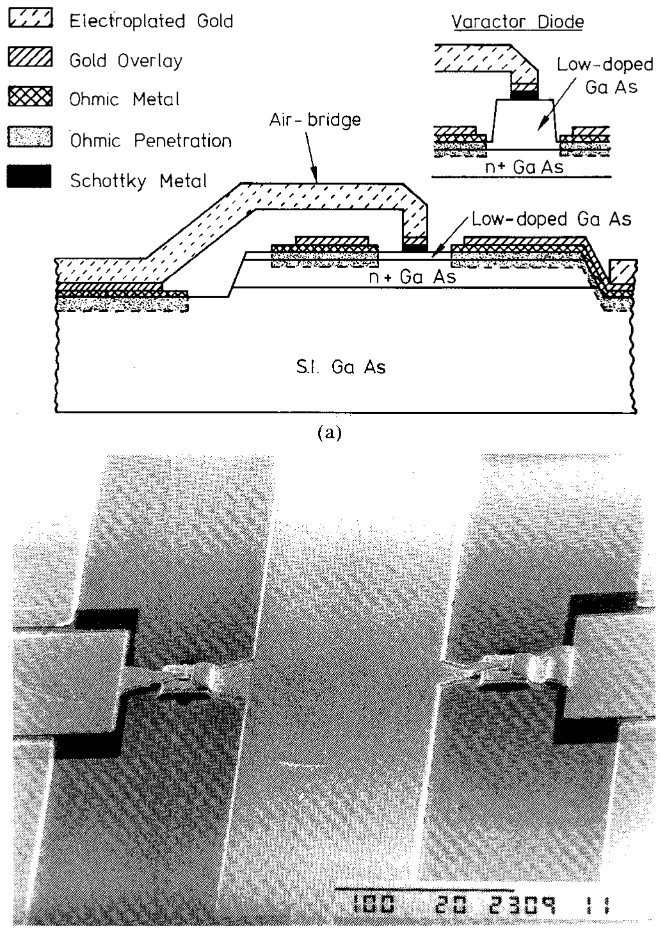


Fig. 1. (a) Cross-sectional view of planar Schottky barrier diodes made at CSIRO, Division of Radiophysics. (b) Scanning electron micrograph of planar Schottky mixer diode.

"whisker" wire used to contact conventional waveguide mounted diode chips [13]. This is achieved in the present design using a gold-plated air bridge, which results in greatly reduced parasitic capacitance when compared with dielectric supported cross-overs [4]–[6]. The air bridge and circuit metal are up-plated to a thickness of 1–2 μm after

a) the deposition of SiO (or Si_3N_4), for passivation of exposed GaAs material between the cathode contact and the anode dot, and for the formation of the dielectric film in metal–insulator–metal sandwich (M–I–M) capacitors; and
b) the definition of the air-bridge feet and capacitor top plates.

With this process, Mott mixer diodes and varactor diodes have been produced simultaneously on the same wafer. The mixer diodes have anodes of 2 μm $\times$ 2 μm and are available both in discrete form and in monolithic microwave integrated circuit mixers. Discrete varactor diodes with anode dimensions of 4 $\times$ 4 μm and 6 $\times$ 6 μm have been produced on the same wafer. To facilitate testing and eventual mounting of the chips, the anode and cathode of the discrete devices are connected to 50-μm-square gold-

TABLE I
PARAMETERS FOR PLANAR SCHOTTKY DIODES FABRICATED AT CSIRO DIVISION OF RADIOPHYSICS

DESIGN

epi-doping = 5 x 10^{16} cm $^{-3}$,
contact layer doping = 2 x 10^{18}cm^{-3},
contact layer thickness = 2μm
zero bias depletion depth = 0.14 μm
predicted parasitic capacitance = 1.76 fF
(50μm x 50μm pads, 100μm substrate, pad spacing was 50μm)

Device Type	Diam. (μm)	Epi Thick. (μm)	Zero Bias Jun.Cap (fF)	Series Resist. (Ω)	Reverse B/down Voltage (volts)
Mixer	2	0.15	3.0	5.9	9.5
Varactor	4	1.0	11.1	27.1	17.5
Varactor	6	1.0	24.1	12.6	17.5

BEST-FIT TO MEASUREMENTS

epi-doping = 8 x 10^{16} cm^{-3},
contact layer doping =2 x 10^{18} cm^{-3}.
zero bias depletion depth = 0.11μm
predicted parasitic capacitance = 1.76fF

Device Type	Diam. (μm)	Epi Thick. (μm)	Zero Bias Jun.Cap (fF)	Series Resist. (Ω)	Reverse B/down Voltage (volts)
Mixer	2	0.18	3.75	10.0	12.3
Varactor	6	0.8	30.07	7.2	12.7

plated pads, with a geometry compatible with the footprint of standard Cascade Microtech wafer probes. The simultaneous production of ultrasmall, very low capacitance mixer diodes, along with high-quality varactor diodes, represents a major achievement of the Division's research program.

III. Diode Characteristics

During the initial design of the planar Schottky diodes, the expected performance was predicted theoretically and the epitaxial material parameters optimized to give the best compromise varactor and mixer diode characteristics on a single wafer. The final design estimates are given in Table I. The predictions of diode zero-bias capacitance, zero-bias depletion depth, breakdown voltage, and series resistance are based on the theory of Setzer [7] and Mattauch and Cregger [8]. The parasitic capacitance is expected to be dominated by the capacitance between the 50-μm-square source contact pads which are spaced 50 μm between edges. The value of this capacitance was calculated by applying the theory of coplanar lines presented by Hoffman [9]. Measurements on a 132$\times$ scale model, using Stycast ($\epsilon_r = 12$) as a dielectric, agreed well with the theoretical prediction ($C_p \sim 2.5$ fF).

Extensive characterization of the dc and microwave behavior of discrete Schottky diodes was carried out at the wafer level. Typical dc performance data for mixer and varactor diodes are summarized in Table II, whereas device uniformity and yield on a sample wafer are shown in Fig. 2. The diode performance, uniformity, and yield are excellent and equivalent to the best results achieved with whisker-contacted devices [13], [15]. As shown in Table I, the discrepancy between the measured performance of the

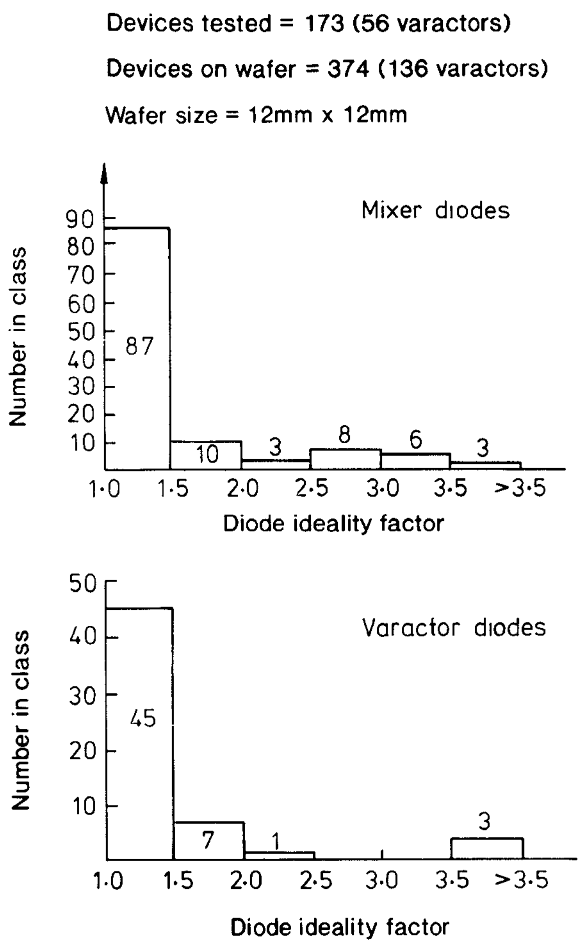


Fig. 2. Uniformity yield statistics for planar Schottky diodes from wafer RPMBE-032.

diodes and the design parameters may be explained by

a) a higher than specified doping, and lower than specified thickness, for the epitaxial layer on the GaAs wafer used; and
b) inadequate control of the epitaxial layer thinning process.

Methods of providing better control of these process variables have been developed and incorporated into recent fabrication runs, resulting in improved diode performance (see below).

The diode dc parameters were determined from computer-aided dc $I-V$ characteristic measurements [10]. A diode response of the form

$$I = I_{\text{sat}}\left(\exp\left(\frac{qV}{\eta kT}\right) - 1\right)$$

where

$$q = 1.602 \times 10^{-19}\ \text{C}$$

$$k = 1.38 \times 10^{-23}\ \text{J/K}$$

was fitted in a least-squares sense to a voltage versus log (current) plot of the measured data. The saturation current (I_{sat}) and the ideality factor (η) were estimated by this method as parameters of the fit. The diode barrier height was determined from these values by

$$V_b = \frac{kT}{q} \ln\left(\frac{AA^*T^2}{I_{\text{sat}}}\right)$$

where A is diode area, A^* is the Richardson constant, and T is the physical temperature.

The series resistance was estimated by measuring the departure of the measured diode response from the ideal curve at high currents. In the present case, the resistance was estimated directly from the residual voltages and also from the derivative of the residuals with respect to diode current.

The parasitic fixed capacitance (associated with the metal pads and interconnects) and the voltage-dependent junction capacitance have been determined using on-wafer microwave measurements (1–18 GHz) of the diode reflection coefficient, as a function of (reverse) bias. A simple equivalent circuit model has been fitted to the data using a Levenberg–Marquadt nonlinear least-squares algorithm [11]. In the equivalent circuit, shown in Fig. 3, the series resistance is assumed to be the dc measured value with an approximate correction for skin effect. In order to achieve lowest estimation error, the parasitic capacitance was determined using measurements on varactor diodes, where the diode capacitance was modulated over a wide range. Estimated parasitic capacitance values are given in Table II.

The exceptionally low parasitic and junction capacitances for the mixer diodes result in cutoff frequencies for these devices which are substantially higher than those previously reported for planar diodes [4]–[6]. The zero bias cutoff frequency for the mixer diodes is of the order of 3500 GHz, comparable to that which can be achieved with the very best whisker-contacted devices. Improvements in the control of the MBE crystal growth and the etching process have resulted in a significant reduction in mixer diode series resistance in recent batches of devices. A resistance of 6 Ω has been achieved with little degradation in yield and without significantly increasing the junction capacitance, with a consequent substantial improvement in zero-bias mixer-diode cutoff frequency.

Typical behavior of the junction capacitance as a function of reverse bias is shown in Fig. 4, for both 2 μm Mott diodes and 6 μm varactor diodes. As expected, the Mott diode junction capacitance is essentially independent of reverse bias, whereas the varactor diode exhibits a half power-law response. The dynamic cutoff frequency for a typical 6 μm varactor diode is 1900 GHz, an outstanding result for a planar diode.

For mixer diodes, an important measure of diode quality is the equivalent noise temperature of the diode measured at microwave frequencies and as a function of current [12]. Typical performance of a CSIRO 2 μm diode is shown in Fig. 5, for diode physical temperatures of 295 K and 77 K, at a frequency of 1.5 GHz. The data have been corrected for the impedance mismatch between the diode and the

TABLE II
TYPICAL MEASURED PARAMETERS FOR CSIRO'S PLANAR SCHOTTKY DIODES FROM WAFER RMBE-032

Device Type	Size (μm)	Device Ident.	T_{amb} (K)	Ideality Factor	Series Resist. (Ω)	Reverse B/down (V@1μA)	Zero-bias Capacit. (fF)	Paras. Capacit. (fF)	Saturation Current (A)
Mixer	2 x 2	6A3	295	1.09	11.3	6.5	3.75±0.6	0.8±0.6	$6x10^{-18}$
			78	1.47	14.1	-	-	-	$5x10^{-44}$
		6C2	295	1.10	13.8	6.9	3.30±0.6	0.75±0.6	1.10^{-17}
		SHM-4.1	295	1.09	13.3	6.7	-	-	$2x10^{-17}$
		SHM-4.2	295	1.09	13.6	6.9	-	-	$1x10^{-17}$
Varactor	6 x 6	3A1	295	1.09	6.5	13.5	33.6±0.4	0.95±0.4	$2x10^{-18}$
		3B1	295	1.09	6.1	13.0	34.5±0.4	0.9 ±0.4	$5x10^{-17}$

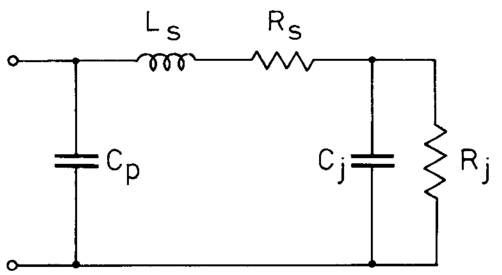


Fig. 3. Equivalent circuit of planar Schottky diode.

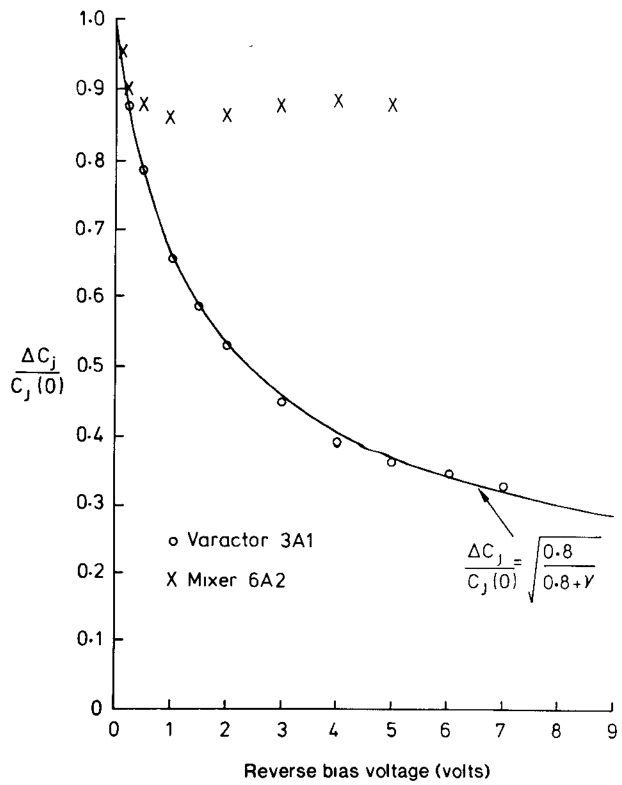


Fig. 4. Typical reverse bias junction capacitance for planar Schottky diodes from wafer RPMBE-032.

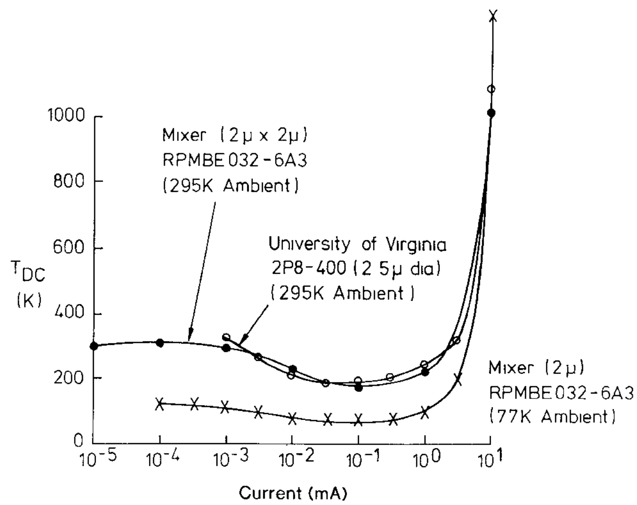


Fig. 5. Typical T_{DC} versus current for planar Schottky diodes.

test radiometer. For comparison, data measured on a high-quality whisker-contact University of Virginia diode at 295 K are plotted on the same graph [13]. The performance is comparable. The cooled data show no evidence of the "camel hump" near 100 μA that has plagued diode fabricators at other laboratories. The minimum noise temperatures are uniformly in good agreement with those predicted from the theory of Viola and Mattauch [12]. The noise from hot-electron effects at high currents is comparable to that observed in the University of Virginia diode.

IV. MILLIMETER-WAVE INTEGRATED CIRCUITS

The planar Schottky diodes have been incorporated in a number of hybrid integrated circuit mixers and frequency multipliers, in order to demonstrate their potential for application in high-performance millimeter-wave systems.

A. Hybrid Single-Ended Mixers

Single-ended mixers for 33–50 GHz and 75–110 GHz have been constructed and tested. The geometrically scaled mixer designs are illustrated in Fig. 6. A 2 μm Mott diode chip (150 μm × 50 μm × 20 μm thick chip) was mounted

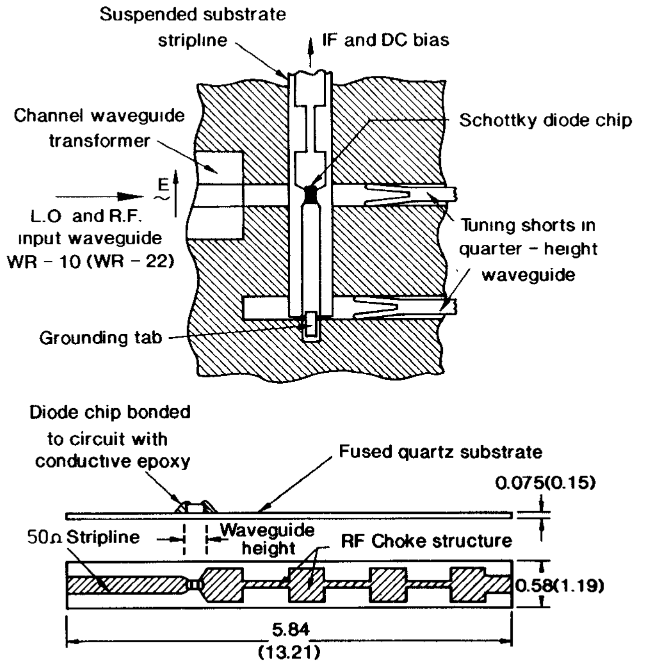


Fig. 6. Simplified diagram showing single-ended mixer using planar diode. Dimensions are in millimetres, with the first dimension applying to the 75–110 GHz mixer mount and the second (bracketed) dimension applying to 33–50 GHz mixer.

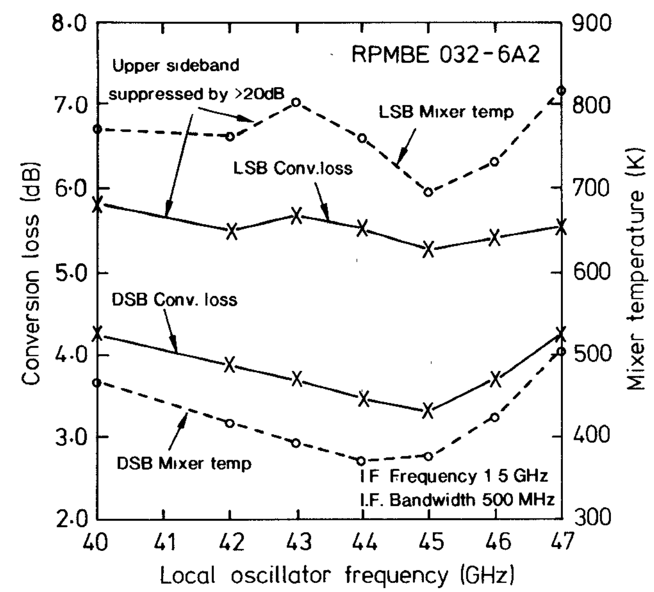


Fig. 7. Performance of hybrid integrated circuit, single-ended mixer using planar Schottky diodes for frequencies 33–50 GHz.

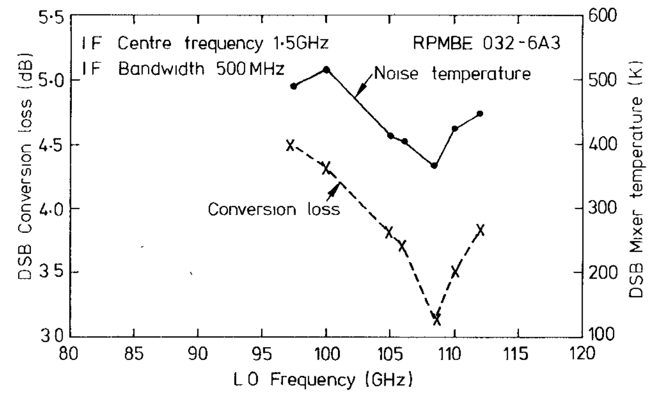


Fig. 8. Performance of hybrid integrated circuit, single-ended mixer using planar Schottky diodes for frequencies 75–110 GHz.

face up on a fused-quartz substrate. Electrical connections were made between the contact pads on the diode chip and the chrome/gold conductor patterns on the quartz using silver-loaded epoxy cement (EPOTEK H20E). The metal patterns on the quartz form suspended-substrate stripline structures for IF/RF filtering, impedance matching, and coupling to the signal waveguides. The signal waveguides, formed in a split copper block, provide two tuning shorts for optimum impedance matching between input waveguide and diode. The design philosophy is similar to that of a mixer circuit proposed by Pan *et al.* [14] for use with superconducting tunnel junctions at millimeter wavelengths.

Computer-automated millimeter-wave test systems have been developed for these measurements in the 33–50 GHz and 75–110 GHz bands [15]. Excellent conversion efficiencies have been obtained over a wide tuning range with these mixers. The mixer performance is summarized in Figs. 7 and 8. Because of the degree of freedom in mixer tuning afforded by the mount design, it is possible to tune either mixer for double-sideband or single-sideband operation. The results reported for single-sideband operation of the 33–50 GHz mixer were measured with image suppression of > 20 dB. The lowest single-sideband conversion loss for this mixer was 5.2 dB at an LO frequency of 40 GHz, operating on the lower sideband, with an IF frequency of 1.5 GHz and an IF bandwidth 500 MHz. The corresponding single-sideband noise figure for this mixer was 5.3 dB. The double-sideband results for this mixer are poorer than would be expected from the single-sideband performance, indicating that the maximum mount bandwidth is less than 3.0 GHz.

The 75–110 GHz results reported are for double-sideband operation, with a sideband ratio which deviated from unity by less than 0.2 dB. The best conversion loss was 3.1 dB double-sideband, at an LO frequency of 106 GHz, with the same IF configuration as reported above. The corresponding double-sideband noise figure was 2.4 dB. When tuned for single-sideband operation at 107.5 GHz and 104.5 GHz, equivalent performance was obtained, indicating that at these frequencies mixer bandwidth does not substantially restrict the double-sideband behavior. The single-sideband response of this mixer has not been measured at other frequencies.

These results represent an advance in the state of the art for hybrid integrated circuit mixers incorporating planar Schottky diodes. Even though the mixers have not been optimized to match the characteristics of the diodes in any way, the conversion losses are substantially lower than reported elsewhere in the literature for comparable mixer structures [4], [16], [17]. Further improvement in performance and bandwidth can be expected with an optimized mount design.

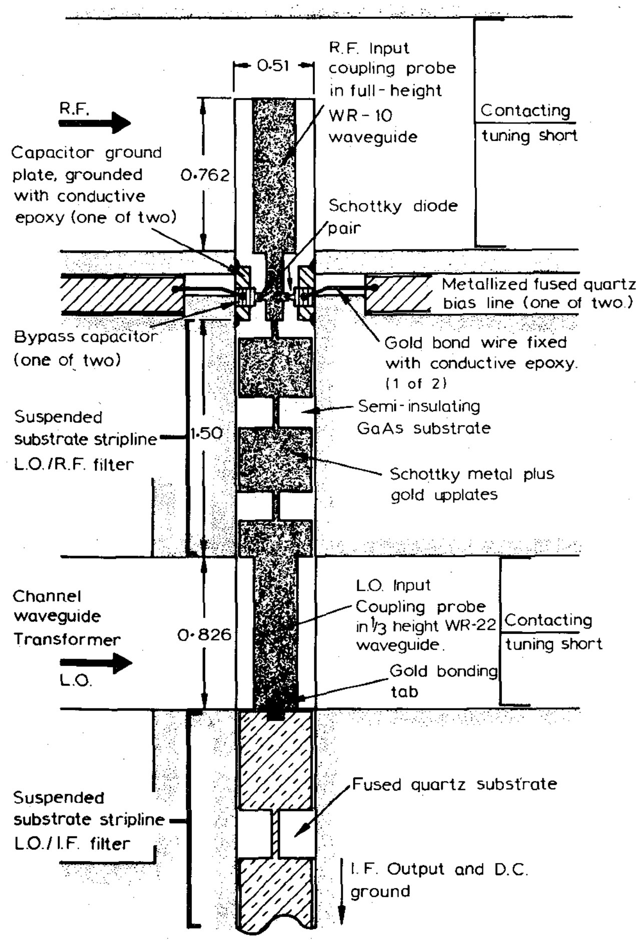


Fig. 9. Cross-sectional diagram of subharmonically pumped mixer mount for 75–110 GHz, incorporating an MMIC active element.

B. Monolithic Integrated Circuit Mixers

A subharmonically pumped MMIC mixer for 75–110 GHz has also been fabricated and tested. The design approach, based on a concept described by McMaster *et al.* [19], is illustrated in Fig. 9. A matched diode pair, transmission line structures for RF/LO filtering and LO/RF matching, and M–I–M capacitors for RF bypassing the individual dc bias input to each diode, are incorporated on a single GaAs substrate. The suspended substrate stripline low-pass filter was based on earlier designs described by Archer [22]. The RF and LO signals are coupled from waveguide inputs to the integrated circuit via backshort-tuned probes (and in the case of the LO signal, via a full height to one-third-height channel–waveguide impedance transformer [21]). IF/LO filtering and dc ground return for the diodes are provided by a separate low-pass filter fabricated on a fused quartz substrate [22], as shown in Fig. 9. Table II demonstrates the excellent match in diode characteristics achieved with these monolithic subharmonic mixers—an undoubted benefit of monolithic circuit integration.

The performance of a typical subharmonically pumped mixer over the frequency range 75–110 GHz is shown in Fig. 10. The conversion efficiency compares well with the best results achieved for hybrid integrated mixers of this type [18], [19]. The minimum double-sideband conversion loss was 5.9 dB at an LO frequency of 43 GHz, with an IF frequency of 1.5 GHz and an IF bandwidth of 500 MHz. The corresponding double-sideband noise figure was 5.6 dB. The development of this subharmonically pumped mixer represents a significant and innovative step toward the realization of monolithically integrated millimeter-wave receiver systems.

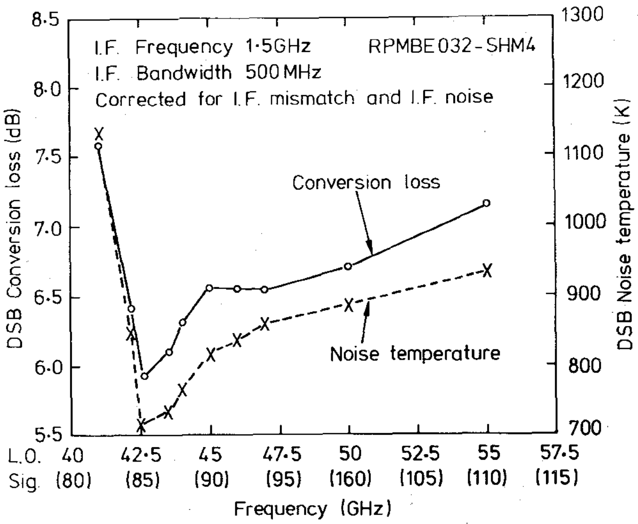


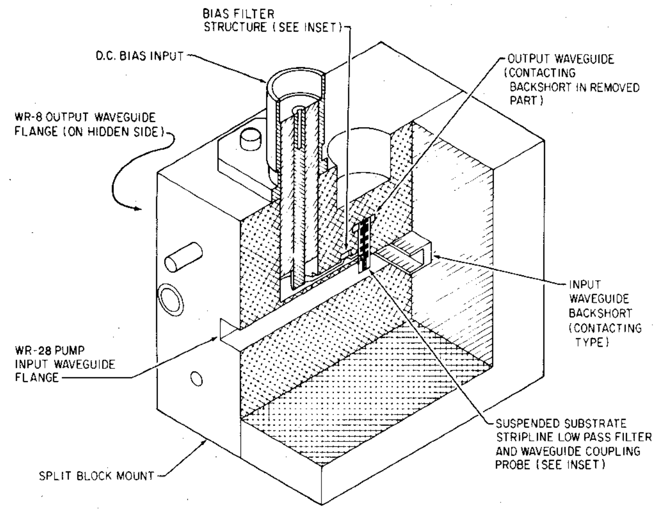
Fig. 10. Performance of the monolithic, subharmonically pumped mixer for frequencies between 80 and 110 GHz.

C. Hybrid Integrated Frequency Tripler

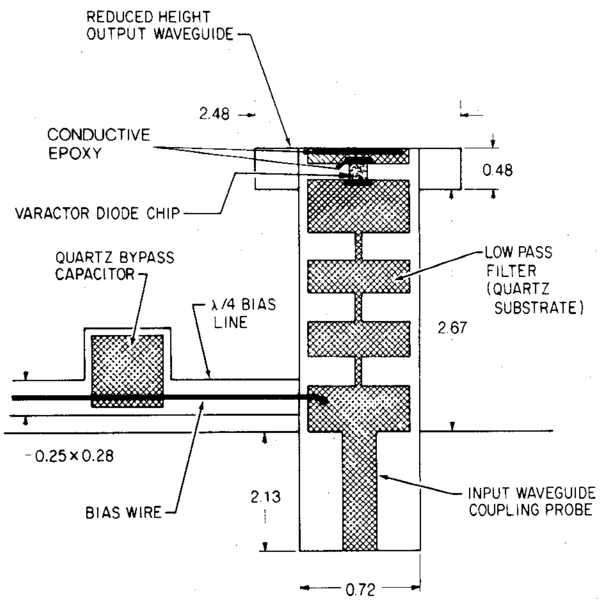
A frequency tripler for 80–120 GHz output has been constructed using a 6 μm planar Schottky varactor diode. The design of the unit is identical to that of a tripler described previously [20], except that the whisker-contacted diode in the original unit has been replaced by the new planar diode, mounted as shown in Fig. 11. The performance of the multiplier is presented in Fig. 12, for output frequencies in the range 80–120 GHz. Backshort tuning and bias were optimized at each measurement frequency. Typical bias conditions for optimum performance were a reverse voltage of 2–3 V and a forward current of 1–4 mA. For 10 mW input power, the minimum conversion efficiency over the measurement band was 5 percent. The peak output power obtained was 1.2 mW at 100 GHz, corresponding to a maximum efficiency of 12 percent. These results are significantly better than those achieved with the earlier version of the multiplier, using a whisker-contacted varactor diode [20].

V. Conclusions

Research at the CSIRO Division of Radiophysics has resulted in the development of improved planar Schottky diodes. The fabrication techniques employed allow the simultaneous realization of ultra-low-capacitance Mott mixer diodes and varactor diodes on the same wafer. The simultaneous processing of HEMT and MESFET circuits incorporating the diodes is possible and is anticipated in the near future. The potential for application of the planar Schottky diodes to high-performance millimeter-wave sys-



(a)



(b)

Fig. 11. (a) Cutaway drawing of the 90–140 GHz frequency tripler mount. (b) Close-up of the quartz substrate, showing filter mounting details and indicating how the planar diode is attached. Dimensions are in millimeters.

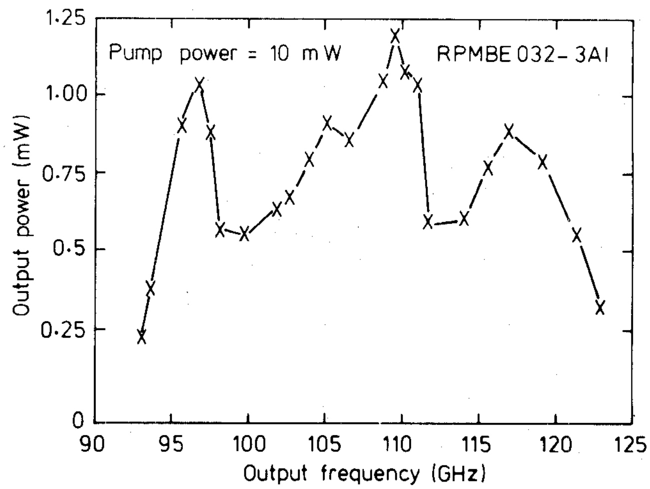


Fig. 12. Performance of the hybrid integrated circuit frequency tripler between 90 and 125 GHz.

tems has been amply demonstrated by the performance of integrated circuit mixers and frequency multipliers incorporating the diodes.

Acknowledgment

The authors wish to thank S. Giugni and G. Griffiths, who grew the epitaxial GaAs upon which the Schottky diodes were fabricated.

References

[1] M. R. Stiglitz, "GaAs technology and MIMIC," *Microwave J.*, vol. 29, pp. 42–62, Sept. 1986.

[2] H. H. Meinel, "Millimeter-wave systems and applications in Europe," in *1988 IEEE MTT-S Int. Microwave Symp. Dig.*, (New York), pp. 649–653.

[3] B. E. Spielman, "Millimeter-wave monolithic integrated circuits," in *1988 IEEE MTT-S Int. Microwave Symp. Dig.*, (New York), pp. 405–408.

[4] W. L. Bishop, K. McKinney, R. J. Mattauch, T. W. Crowe, and G. Green, "A novel whiskerless diode for millimeter and submillimeter wave applications," in *1987 IEEE MTT-S Int. Microwave Symp. Dig.*, (Las Vegas, NV), pp. 607–610.

[5] U. K. Mishra, S. L. Palmateer, S. J. Nightingale, M. A. G. Upton, and P. M. Smith, "Surface-oriented, low-parasitic Mott diode for EHF mixer applications," *Electron. Lett.*, vol. 21, pp. 652–653, July 1985.

[6] J. S. K. Mills and F. Azan, "Design, fabrication and applications examined for mm-wave GaAs beam-lead Schottky diodes," *Microwave Syst. News*, vol. 17, no. 8, pp. 46–59, Aug. 1987.

[7] C. S. Setzer, "Development and characterization of the flip chip diode," Ph.D. dissertation, University of Virginia, pp. 102–123, Jan. 1981.

[8] R. J. Mattauch and B. B. Cregger, "The design of high-efficiency abrupt junction varactor diodes for millimeter wavelengths applications," Interim Report to National Science Foundation under contract ECS80-22937, pp. 12–58, May 1982.

[9] R. K. Hoffman, *Handbook of Microwave Integrated Circuits*. Norwood, MA: Artech House, 1987, pp. 364–367.

[10] S. K. Cheung and N. W. Cheung, "Extraction of Schottky diode parameters from forward current voltage characteristics," *Appl. Phys. Lett.*, vol. 49, no. 2, pp. 85–87, 14 July 1986.

[11] D. W. Marquadt, "An algorithm for least squares estimation of non-linear parameters," *SIAM J. Appl. Math.*, vol. 11, no. 2, 1963.

[12] T. J. Viola and R. J. Mattauch, "Unified theory of high frequency noise in Schottky barriers," *J. Appl. Phys.*, vol. 44, no. 6, pp. 2805–2815, June 1973.

[13] J. W. Archer and M. T. Faber, "Low-noise, fixed-tuned broadband mixer for 200–270 GHz," *Microwave J.*, vol. 27, no. 7, pp. 135–140, July 1984.

[14] S. K. Pan, M. J. Feldman and A. R. Kerr, "A low-noise 115 GHz receiver using superconducting tunnel junctions," *Appl. Phys. Lett.*, vol. 43, pp. 786–788, 1983.

[15] M. T. Faber and J. W. Archer, "Computer-aided testing of mixers between 90 and 350 GHz," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, pp. 1133–1145, Nov. 1985.

[16] B. Jarry, J. S. K. Mills, and F. Azan, "94 GHz microstrip monolithic GaAs mixer," *Electron. Lett.*, vol. 22, pp. 1328–1329, Dec. 4, 1986.

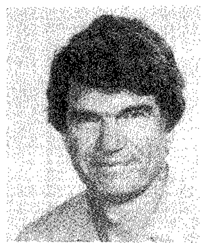
[17] N. J. Cronin and V. J. Law, "Planar millimeter-wave diode mixer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 827–830, Sept. 1985.

[18] R. S. Tahim, T. Pham, and P. Yen, "*W*-band low-noise integrated circuit sub-harmonically pumped mixer with over 10 GHz instantaneous R.F. bandwidth," *Microwave J.*, vol. 29, no. 7, pp. 157–162, July 1986.

[19] T. F. McMaster, M. V. Schneider, and W. W. Snell, "Millimeter-wave receivers with sub-harmonic pump," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-24, pp. 948–952, 1976.
[20] J. W. Archer and M. J. Crawford, "A synthesized 90–120 GHz signal source," *Microwave J.*, vol. 28, no. 5, pp. 227–255, May 1985.
[21] P. H. Siegel, D. W. Peterson, and A. R. Kerr, "Design and analysis of the channel waveguide transformer," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, pp. 473–484, June 1983.
[22] J. W. Archer, "An efficient 200–290 GHz frequency tripler incorporating a novel stripline structure," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-32, pp. 416–420, Apr. 1984.

John W. Archer (M'82–SM'83) was born in Sydney, Australia, in 1950. He received the B.S.c, B.E. (Hons I), and Ph.D. degrees from Sydney University in 1970, 1972, and 1977 respectively. His Ph.D. led, in 1977, to the development of the first 100 GHz variable-baseline, two-element coherent interferometer for radio astronomy (a joint CSIRO/Sydney University project).

From 1977 to 1985 he was employed by the National Radio Astronomy Observatory in the U.S. The initial two years was spent working on the VLA project, where he was responsible for improvements to the performance of the millimetre-wave waveguide communications system, as well as the design of components for the IF section of the array. The last four years were spent at NRAO's central development laboratory developing state-of-the-art millimetre-wave receiver technology for the Kitt Peak antenna in Arizona. Since 1985 he has been with CSIRO Division of Radiophysics as Leader of the Solid-State Devices Programme. He has been responsible for the planning and execution of an $8m research effort to develop and ultimately commercialize microwave and millimetre-wave GaAs technology in Australia. As well as providing leadership and contributing to a number of significant research achievements, he has promoted the successful founding of a new company, Triune Pty Ltd, which will manufacture and market products derived from the division's research.



Robert A. Batchelor was born in Sydney, Australia, on July 22, 1937. He obtained the Diploma of Radio Engineering and the B.E. (Hons II) degree from the University of New South Wales in 1959 and 1961, respectively.

Between 1959 and 1963 he was involved in radio and TV receiver design at Kriesler Ásia Pty Ltd. Since 1963 he has been employed at the CSIRO Division of Radiophysics, engaging in radio astronomy and radio astronomy receiver design, at frequencies up to 115 GHz. Since 1985 he has been a member of the Division's Solid-State Devices Group, contributing to the design and evaluation of low-noise devices.

C. J. Smith, photograph and biography not available at the time of publication.