planar transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 2125–2131, Dec. 1982.
[4] W. J. Getsinger, "Microstrip dispersion model," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-21, pp. 34–39, Jan. 1973.
[5] T. C. Edwards and R. P. Owens, "2-18 GHz dispersion measurements on 10-100 ohm microstrip lines on sapphire," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-24, pp. 506–513, Aug. 1976.
[6] M. V. Schneider, "Microstrip dispersion," *Proc. IEEE*, vol. 60, pp. 144–146, Jan. 1972.
[7] M. Kobayashi, "Important role of inflection frequency in the dispersive property of microstrip lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-30, pp. 2057–2059, Nov. 1982.
[8] K. C. Gupta, R. Garg, and I. J. Bahl, *Microstrip Lines and Slotlines*. Dedham, MA: Artech House, 1979, p. 91.
[9] G. Kompa and R. Mehran, "Planar waveguide model for calculating microstrip components," *Electron. Lett.*, vol. 11, pp. 459–460, 1975.
[10] R. P. Owens, "Predicted frequency dependence of microstrip characteristic impedance using the planar wave-guide model," *Electron. Lett*, vol. 12, pp. 269–270, 1976.
[11] H. F. Pues and A. R. van de Capelle, "Approximate formulas for frequency dependence of microstrip parameters," *Electron. Lett.*, vol. 16, no. 23, pp. 870–872, 1980.
[12] P. Pramanick and P. Bhartia, "Frequency dependence of effective width of planar waveguide model for microstrips," submitted for publication.
[13] J. B. Knorr and A. Tufekcioglu, "Spectral-domain calculation of microstrip characteristic impedance," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 725–728, 1975.
[14] R. H. Jansen and M. Kirsching, "Arguments and an accurate model for the power current formulation of microstrip characteristic impedance," *Arch. Elek. Ubertragung*, vol. 37, pp. 108–112, 1983.
[15] W. J. Getsinger, "Measurement and modelling of apparent characteristic impedance of microstrip," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-31, pp. 624–632, Aug. 1983.
[16] R. M. Knox and P. P. Toulios, "Integrated circuits for the millimeter through optical frequency range," in *Proc. Symp. on Submillimeter Waves*. Brooklyn, NY, Polytechnic Press of Polytechnic Inst., 1976, pp. 497–516.
[17] H. A. Wheeler, "Transmission line properties of parallel strips separated by a dielectric sheet," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, pp. 280–289, Mar. 1964.
[18] M. V. Schneider, "Microstrip lines for microwave integrated circuits," *Bell Syst. Tech. J.*, vol. 48, no. 3, pp. 1421–1444, 1969.
[19] E. J. Denlinger, "A frequency dependent solution for microstrip transmission lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 30–39, Jan. 1971.
[20] R. Mittra and T. Itoh, *Advances in Microwaves*. New York: Academic, 1974.
[21] R. Mittra and T. Itoh, "A new technique for the analysis of the dispersion characteristics in microstrip lines," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-19, pp. 47–56, Jan. 1971.
[22] E O. Hammerstad and Ø. Jensen, "Accurate models for microstrip computer aided design," in *IEEE MTT-S Int. Microwave Symp. Dig.*, 1980, pp. 407–409.
[23] B. Bianco, L. Panini, M. Parodi, and S. Ridella, "Some considerations about the frequency dependence of the characteristic impedance of uniform microstrips," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 182–185, Mar. 1978.

Microwave Point Contact Diode Responsivity Improvement through Surface Effects in Vacuum

N. S. KOPEIKA, SENIOR MEMBER, IEEE, ISRAEL HIRSH, AND M. RAVFOGEL

***Abstract* —Desorption of air atoms from point contact diode surfaces via exposure to vacuum can give rise to significant changes in electronic characteristics. In the example considered, exposure of an X-band detector to a modest vacuum gives rise to a responsivity increase of about 80 percent for video and heterodyne detection. Experiments indicate that vacuum desorption of minority surface impurities increases the barrier height and decreases tunneling probability, thus increasing diode nonlinearity and making the diodes more nearly "ideal." The resulting relative increase of the thermionic emission current should decrease the effective shot-noise temperature, thus increasing the signal-to-noise ratio (SNR) even further.**

Manuscript received January 4, 1984; revised May 10, 1984.
The authors are with the Department of Electrical and Computer Engineering, Ben-Gurion University of the Negev, Beer-Sheva, Israel 84120.

I. Introduction

Recent experiments with light emitting diodes (LED's) [1] and photodiodes [2] have indicated that, despite "hermetic sealing," immersion of such devices in even modest vacuums for several hours or even days gives rise to desorption of surface-adsorbed gases from passivation layers and to subsequent semiconductor free charge carrier diffusion and redistribution which significantly alter diode electronic and optical properties. Changes in the current–voltage ($I-V$) and capacitance–voltage ($C-V$) characteristics reflect the loss in charge which previously had been contributed by adsorbed gas atoms that had now been desorbed. Resulting free charge redistribution can alter significantly the effective junction depletion layer width both at the surface and in the bulk. For surface-emitting LED's, these can involve significant wavelength tuning through changes in surface bandbending [1], [2]. For photodiodes, significant quantum efficiency improvement is obtainable as a result of reduced surface recombination [3]. In view of such significant alterations in p-n optoelectronic diode properties under vacuum, a preliminary investigation was launched as to effects of vacuum on electronic and microwave detection properties of point contact diodes. In the latter, the metal–semiconductor surface is much more exposed than in evaporated metal Schottky barrier devices. The experimental results indicate significant changes in point contact diode electronic properties have indeed occurred. In vacuums on the order of only 0.05 torr, microwave responsivity is on the order of 80 percent greater than that in the open air, for both video and heterodyne detection.

II. Experiments

The diodes used in these experiments were *thermocompression bonded* IN23C point contact cartridge mixer X-band detectors manufactured by Microwave Associates, Inc. (The choice was based entirely on convenience—these were available in quantity in our facility.) Like the diodes of [1]–[3], they are *supposed to be* "hermetically sealed." Nevertheless, these point contact diodes *also* exhibited significant changes resulting from prolonged exposure to vacuum conditions. Since internal fabrication details are unknown to us, this work will concentrate on *changes* in diode parameters brought about by a vacuum environment, rather than on the actual parameters themselves. The diodes were placed in a 3-cm-diameter cylindrical experimental metal cell attached to a vacuum system, described in detail in [1]. Diode length was aligned parallel to the incident RF electric field. Closing this cell was a glass window of 2-cm diameter through which the X-band radiation could propagate into the cell. The aperture diameter was sufficiently large so as to permit propagation through it at these wavelengths. All experiments, including those at atmospheric pressure air, took place with the diodes in the experimental cell. The only difference in the experiments was the air pressure within the cell.

Forward and reverse $I-V$ characteristics are compared at atmospheric pressure air and under vacuum conditions in Figs. 1 and 2. Although reverse-bias conductivity decreases in vacuum, the opposite is true under forward-bias conditions. Since device

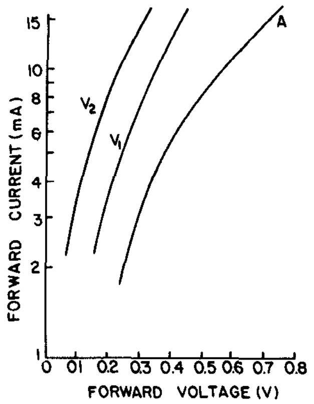

Fig. 1. Forward-bias $I-V$ characteristics of 1N23C-point contact X-band detector. A is atmospheric pressure air. V_1 and V_2 are after immersion in 5×10^{-2}-torr air for 5 h and 1 week, respectively.

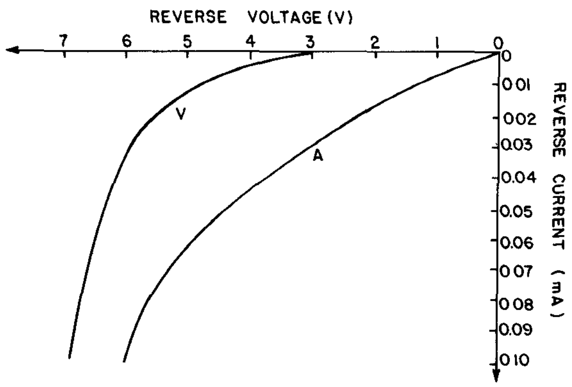

Fig. 2. Reverse-bias $I-V$ characteristic of 1N23C diode in atmospheric pressure air A and after 1 day in 5×10^{-2}-torr air V.

power consumption is considerably greater in forward bias, and since dissipation of heat is reduced under vacuum conditions, in order to evaluate possible effects of desorption it is necessary to consider device heating effects. Hence, the diodes were heated in an oven and forward $I-V$ characteristics compared, as shown in Fig. 3. Device heating shifts the $I-V$ characteristics to the left, but also decreases noticeably the forward slope, as expected from theory. Fig. 1 indicates, however, that in vacuum the $I-V$ slope is increased. The shift to the left in vacuum may be a result of increased device heating. The increased forward slope, however, is not. The latter is significant application-wise too, since the *increased nonlinearity under vacuum conditions suggests improved rectification properties*. This was indeed verified experimentally. Unbiased diode response to about 200 μW$\cdot$cm^{-2} of 1-kHz pulsed X-band irradiance (at 9.26 GHz) was measured with the experimental cell at atmospheric pressure. A plot of video signal versus attenuation is shown in Fig. 4. The cell was exposed to vacuum ($\sim$ 0.05 torr) for about one week. Using a reference diode and an attenuator to insure incident X-band power was the same, the experiment was repeated under identical experimental conditions but with the test diodes under vacuum. Diode response is seen in Fig. 4 to be almost 80 percent higher under vacuum. The experiment was repeated using two klystrons phase locked as described in [4]. The intermediate frequency was 200 kHz. The improvement in diode response under vacuum was similar. In order to consider further the internal changes in the diode brought about by a vacuum environment, the diode capacitance was measured at 1 MHz under both atmospheric pressure and vacuum conditions, as shown in Fig. 5.

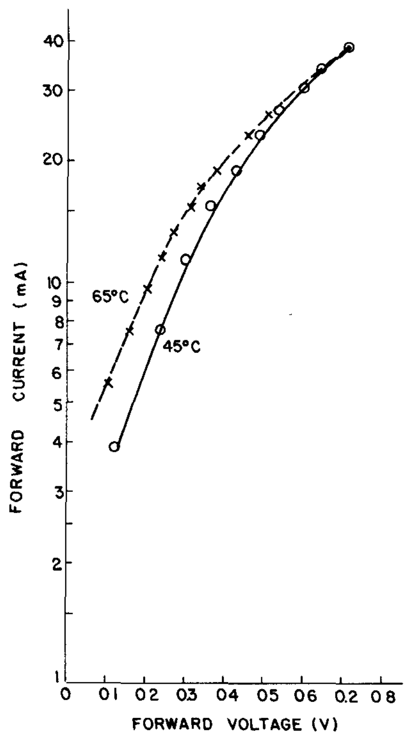

Fig. 3. Forward-bias $I-V$ characteristics of 1N23C diode at ambient temperatures of 45 and 65°C at atmospheric pressure.

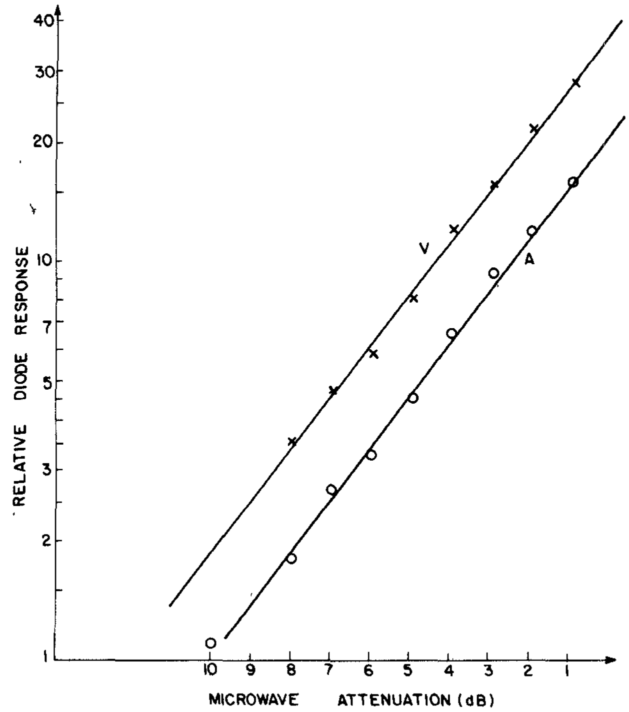

Fig. 4. 1N23C diode response at 9.26 GHz when diode is at atmospheric A and 0.05-torr V pressure air. Maximum irradiance is about 200 μW$\cdot$cm^{-2}. Diode is unibased.

Exposure of diodes to open atmosphere after vacuum exposure resulted, after several days, in a return to electronic and detection properties measured prior to vacuum exposure. This suggests it is *atoms* from the air that are desorbed and adsorbed with reduced and increased air pressure, respectively.

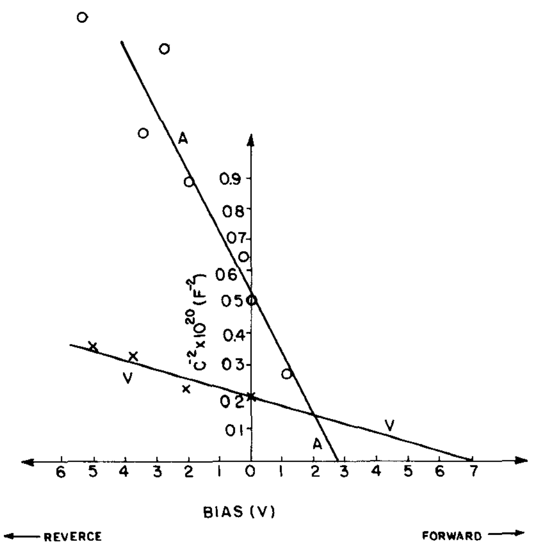

Fig. 5. 1N23C diode capacitance^{-2} versus voltage at 1 MHz at atmospheric A and 0.05-torr V pressure air. (Capacitance measurements are not normalized to diode area. Therefore, voltage intercepts do not represent barrier heights.)

III. Discussion

The changes in electronic and rectification properties induced by prolonged vacuum immersion are evident in Figs. 1–5. To explain them, several possible causes have to be considered. It is conceivable, for example, that mechanical or pressure effects changing the stress on the whisker can play some role in these vacuum-induced changes. Vacuum operation implies decreased stress. The fact that these diodes are "thermal compression" bonded, according to manufacturer's data sheets, suggests, however, that such effects are not significant here. It is also well known that hydrostatic pressure effects on semiconductor energy gaps are rather small and generally require thousands of atmospheres of pressure change in order to be noticeable [1], [5], [6]. In the present case, the pressure change is from 1 atm to modest vacuum, a pressure change of only 1 atm at most. Thus, such pressure effects are hardly likely to affect the very noticeable changes here. Uniaxial stress, however, is known to produce significant changes in p-n diode characteristics, particularly in Si. The breakdown voltage in Si, furthermore, is linearly related to uniaxial compression stress. The proportionality factor is of the same order of magnitude as the bandgap dependence on hydrostatic pressure [6]. For the 1-atm change here, there should be no noticeable change in breakdown voltage resulting from uniaxial stress. Fig. 2 indicates noticeable change in breakdown voltage. This cannot be explained on the basis of pressure. Furthermore, as seen from Fig. 1, the vacuum immersion effects involve very slow processes. The prolonged time periods of days to a week of vacuum immersion in order for steady-state changes to stabilize are much too slow to be explained by pressure or thermal effects. However, vacuum desorption of surface adsorbed gases and subsequent free charge carrier diffusion and redistribution can be expected to be very slow processes, as has indeed been found to occur with optoelectronic devices as described in the introduction of this paper. Thus, without entirely ruling out possible pressure or thermal effects, the vacuum-induced changes reported here will be approached from the point of view of desorption and subsequent free charge carrier diffusion and redistribution. A self-consistent hypothesis emerges supported by all the various *independent* measuremens of diode properties described above that can explain the vacuum-induced changes.

The forward current density J for a Schottky barrier diode is usually written as [7]

$$J = J_s \exp(qV/nkT)[1-\exp(-qV/kT)] \tag{1}$$

where V is forward voltage, k is Boltzman's constant, T is temperature (°K), n is the ideality factor, and J_s is the saturation current usually described for pure thermionic emission as [7]

$$J_s = A^{**}T^2 \exp(-q\phi_{b0}/kT) \tag{2}$$

where A^{**} is the modified Richardson constant and ϕ_{b0} is barrier height under zero-bias conditions. Equation (2) indicates that the saturation current increases with increased temperature. Since the saturation current here does *not* increase in vacuum without increased self-heating (Fig. 2), device heating must therefore be responsible for the $I-V$ shift to the left in Fig. 1. Indeed, without noticeable temperature increase, the saturation current is seen in reverse bias to *decrease* in vacuum. This decrease suggests from (2) that, under vacuum, the barrier height has increased. This hypothesis is supported by the independent $C-V$ measurements in Fig. 5, which indicate that the intercept on the voltage axis has increased in vacuum. The increase of the voltage intercept requires a corresponding increase in barrier height and implies that, in the semiconductor material, the effect of vacuum ambient is to move the Fermi level further away from the energy gap center. This increases the barrier [8]. In other words, the impurity concentration of the semiconductor has *effectively* increased as a result of vacuum ambient. This suggests that the atoms desorbed through vacuum immersion which had previously been adsorbed in open air were of minority impurity type. The slope decrease in Fig. 5 for vacuum indicates an effective increase of majority impurities by a factor of almost seven. Because the diode area is unknown, neither $I-V$ nor $C-V$ data can be used to determine the actual barrier height; however, the relative changes in barrier height induced by prolonged vacuum immersion are quite evident in the independently measured data of both Figs. 2 and 5.

This hypothesis of barrier height increase in vacuum is strengthened when the physical significance of vacuum operation on the $I-V$ forward slope is considered. When $n=1$, the forward current is a purely thermionic emission. Increases of n indicate increased tunneling. The effect of tunneling on $I-V$ characteristics is to decrease the forward slope and to increase reverse-bias conductivity [9]. Comparison of Figs. 1 and 2 indicates the opposite occurs in vacuum and therefore tunneling in vacuum is significantly decreased in this case. In particular, the increased slope in Fig. 1 for vacuum requires (nT) in (1) to decrease. Because T increases for forward bias in vacuum (Fig. 1) and decreases the slope as expected from (1), the nT decrease must be entirely that of n. *The diode has become much more nearly "ideal."* Vacuum-induced changes in n are summarized in Table I. Tunneling decrease (from forward $I-V$ slope—Fig. 1 and Table I) is consistent with increased barrier height (reverse-bias $I-V$ and $C-V$ data—Fig. 2. and Fig. 5). Thus, all three independent measurements support the same hypothesis of barrier increase in vacuum. Since [7]

$$\frac{1}{n} = 1 - \frac{\partial\phi_b}{\partial V} \tag{3}$$

where ϕ_b is the barrier height for bias V, the decrease of n in vacuum suggests that the barrier, and thus J_s, should vary less with voltage in vacuum than they do at atmospheric pressure. This is indeed supported by the reverse $I-V$ curve of Fig. 2 where power consumption and, thus device heating, are considerably less than at forward bias.

TABLE I
TYPICAL CHANGES IN n INDUCED BY VACUUM OPERATION (n_0 IS IDEALITY FACTOR AT ATMOSPHERIC PRESSURE)

air pressure	$\frac{n}{n_0}$
open air	1
after 5 hrs. of .05 torr air immersion	0.66
after 1 week of .05 torr air immersion	0.55

Fig. 2 indicates barrier lowering due to the field is less in vacuum. This is also readily understood in terms of desorption. Adsorbed gas atoms are bonded rather weakly to the surface. Because of the weak bonds, impurities contributed by them to the semiconductor material are generally at *shallow* energy levels. These surface population states are thus much more susceptible to changes with bias. Fig. 2 is thus also consistent with the concept of desorption.

The increased barrier in vacuum would appear to be directly responsible for the tunneling decrease [9]. Similar experimental results were obtained with IN23B diodes.

As regards detection applications, it is also of interest to note that, as the current approaches pure thermionic emission, equivalent shot-noise temperature is known to decrease [9], thus increasing the signal-to-noise ratio (SNR) even further. Furthermore, the vacuum levels used in this study are quite modest. Desorption is known to vary linearly with pressure [10]–[13]. Consequently, further reductions in pressure should increase the barrier height still further. However, since barrier width also affects tunneling probability, it does not necessarily follow that lowest ambient pressure necessarily makes the diode more nearly ideal. No effort was made to determine vacuum pressure at which SNR is optimized.

This work indicates that conductivity, capacitance, and video detection and mixing sensitivity can be noticeably affected by surface effects such as *changing ambient pressure*. These should be considered in high altitude and space applications, as well as in packaging techniques.

REFERENCES

[1] N. S. Kopeika, H. Aharoni, I. Hirsh, S. Hava, and I. Lupo, "Wavelength tuning of GaAs LEDs through surface effects," *IEEE Trans. Electron. Device*, vol. ED-30, pp. 334–347, Apr. 1983.

[2] N. S. Kopeika, S. Hava, and I. Hirsh, "Gamma ray irradiated LED's: Surface emission and significant wavelength tuning through surface states," *IEEE J. Quantum Electron.*, vol. QE-20, pp. 63–71, Jan. 1984.

[3] N. S. Kopeika, I. Hirsh, and E. Hazout, "Significant photodiode quantum efficiency improvement and spectral response alteration through surface effects in vacuum," *IEEE Trans. Electron Devices*, vol. ED-31, pp. 1198–1205, Sept. 1984.

[4] Y. Makover, O. R. Manor, and N. S. Kopeika, "Very high sensitivity heterodyne detection of *X*-band radiation with neon indicator lamps," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-26, pp. 38–41, Jan. 1978.

[5] Y. Kanda, "Effect of stress on germanium and silicon p-n junctions," *Japan J. Appl. Phys.*, vol. 6, pp. 475–486, Apr. 1967.

[6] J. R. Hauser and J. J. Wortman, "Some effects of mechanical stress on the breakdown voltage of p-n junctions," *J. Appl. Phys.*, vol. 37, pp. 3884–3892, Sept. 1966.

[7] E. H. Rhoderick, "Metal–semiconductor contacts," *Inst. Elec. Eng. Proc.*, vol. 129, pt. 1, pp. 1–14, Feb. 1982.

[8] V. L. Rideout, "A review of the theory, technology and applications of metal-semiconductor rectifiers," *Thin Solid Films*, vol. 48, pp. 261–291.

[9] M. V. Schneider, "Electrical characteristics of metal–semiconductor junctions," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-28, pp. 1169–1173, Nov. 1980.

[10] P. A. Redhead, "Thermal desorption of gases," *Vacuum*, vol. 13, pp. 203–211, 1962.

[11] J. T. Law, "The adsorption of water vapor on germanium and germanium dioxide," *J. Phys. Chem.*, vol. 59, pp. 62–71, Jan. 1955.

[12] J. T. Law, "The adsorption of gases on a germanium surface," *J. Phys. Chem.*, vol. 59, pp. 543–548, June 1955.

[13] R. H. Kingston, "Water vapor induced n-type surface conductivity on p-type germanium," *Phys. Rev.*, vol. 98, pp. 1766–1775, June 1955.

Effect of Inner Conductor Offset in a Coplanar Waveguide

KOHJI KOSHIJI AND EIMEI SHU

Abstract—**This paper reports on the effect of structural offset in a coplanar waveguide on the characteristic impedance and line loss. This effect can be an appreciable factor in designing highly precise circuits, such as MIC's using coplanar waveguide, or a coplanar-type standing-wave detector.**

The electric field over the cross section of the line is analyzed by assuming a TEM mode of wave propagation, and solving a two-dimensional Laplace's equation by means of the successive over-relaxation method. In the analysis, an approximate solution based on symmetry is employed. Also, measurements are made to confirm the results thus obtained.

I. INTRODUCTION

Coplanar waveguides are so composed as to make it especially convenient for constructing nonreciprocal circuit elements using magnetic substrates, as well as active circuit elements employing transistors and diodes.

Studies on the fundamental characteristics of coplanar waveguides have been made by C. P. Wen [1], T. Hatsuda [2], M. E. Davis *et al.* [3], J. B. Knorr *et al.* [4], Y. Fujiki *et al.* [5], and the authors [6]–[8]. This paper reports on the effect of structural offset in a coplanar waveguide on the line characteristics. This effect constitutes an appreciable factor in designing highly precise circuits, such as MIC's using coplanar waveguide or a coplanar-type standing-wave detector. In this report, changes in the characteristic impedance and line losses as a result of offset are evaluated by solving Laplace's equation. Computer solution of Laplace's equation is conducted by means of the successive over-relaxation method. Also, measurements are made to confirm the results obtained.

II. METHOD OF ANALYSIS

Fig. 1 shows the cross section of a coplanar waveguide, in which the width of the inner conductor is denoted by $2w$, the spacings between the inner and the outer conductors by s_1 and s_2, and the thickness of the conductors by $2t$. The conductors are supported by a dielectric substrate of thickness d, relative permittivity ϵ_r, and unit relative permeability.

The first step of the analysis is to determine the electric field over the cross section of the line. This problem can be reduced to that of a two-dimensional static field if we assume a TEM mode

Manuscript received August 12, 1983; revised April 13, 1984.

The authors are with the Faculty of Science and Technology, Science University of Tokyo, Noda-shi, 278, Japan.

0018-9480/84/1000-1387$01.00 ©1984 IEEE