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D-Band Subharmonic Mixer with Silicon Planar Doped Barrier Diodes

Ulrich Güttich, Karl M. Strohm, and Friedrich Schäffler

***Abstract*—A subharmonically pumped mixer for RF frequencies in the D-band range has been realized applying silicon planar doped barrier (PDB) diodes grown by molecular beam epitaxy (MBE). Excellent RF performance data have been achieved with a finline/microstrip mixer design.**

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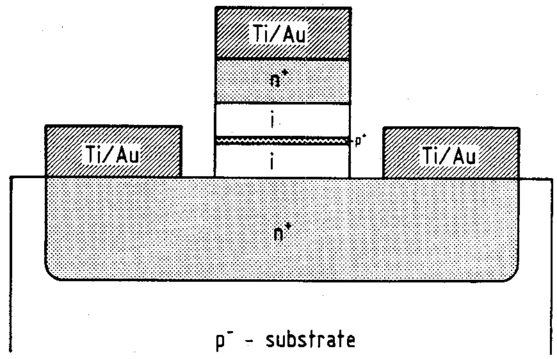

Fig. 1. Schematic cross section of PDB diode with active layer sequence and ohmic contacts.

I. INTRODUCTION

Subharmonically pumped integrated mixers (SHM's) offer many advantages over conventional down-converters, particularly at elevated RF frequencies, where local oscillator pump power and phase noise requirements are difficult to attain. SHM's realized as a finline or microstrip configuration [1], [2] have demonstrated conversion loss and noise comparable to the best fundamental balanced mixers up to 100 GHz. However, Schottky diode pairs conventionally applied in SHM's have to be matched very carefully to minimize loop inductance effects [3]. This problem can be overcome by employing planar doped barrier (PDB) diodes [4], the symmetric $I-V$ characteristic of which is an inherent property of the device and not the result of matching two separate antiparallel diodes. In addition, the required LO pump power can be reduced by lowering the barrier height of the device to a value much smaller than that of a Schottky diode. Furthermore, designing the mixer circuit is simplified since only one device, instead of two antiparallel connected diodes, is involved. The advent of molecular beam epitaxial (MBE) growth techniques now has enabled silicon PDB structures (n^+-i-p^+-i-n^+) to be grown for applications up to 140 GHz.

II. DIODE PROCESSING AND DC CHARACTERISTICS

The PDB diodes are fabricated on high-resistivity silicon substrates (p-type, resistivity $> 3000\ \Omega \cdot$cm) in a coplanar configuration. First, oxide windows are defined and highly doped n^+ buried regions are established using an As double implantation and diffusion process (sheet resistance $< 7\ \Omega$ per square, carrier concentration $> 10^{20}$ cm^{-3}). The doping profile is realized by silicon MBE growth. The PDB is a majority carrier device structure with an extremely thin and fully depleted p^+ acceptor layer to form a triangular potential profile of predetermined shape and height. For a subharmonic mixer, a symmetric $I-V$ characteristic is required and therefore the acceptor p^+ layer has to be positioned in the center of the undoped intrinsic region (Fig. 1). The design of the doping profile is calculated using formulas reported in [5]. The epitaxial process is performed in an ATOMIKA Si-MBE machine described in detail elsewhere [6]. Growth commences with a highly n-doped (Sb, typically $> 2 \cdot 10^{18}$ cm^{-3}) buffer layer of about 20 nm thickness. The barrier structure itself consists of a p-type doping spike of 10 to 20 nm thickness between two equally wide, nominally undoped layers. Gallium evaporated from a conventional effusion cell is used as spike acceptor material. Doping by secondary implantation is employed to achieve the required doping levels and abruptness. A 0.2-μm-thick n^+ top layer used for the

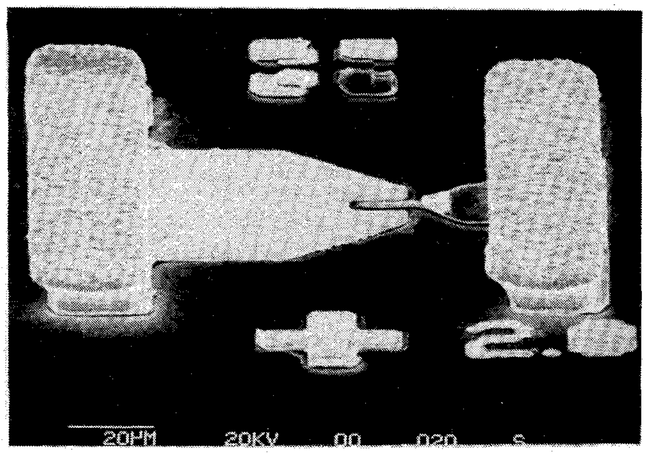

Fig. 2. Scanning electron micrograph of a coplanar PDB diode.

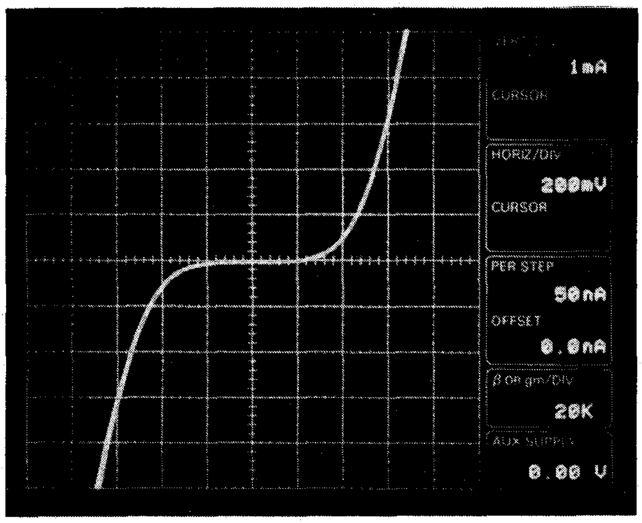

Fig. 3. Current–voltage characteristic of PDB diode C0681.

fabrication of the upper ohmic contact is Sb-doped to a concentration of about 10^{20} cm^{-3}. After the growth of the MBE layers the upper ohmic finger contact is defined by evaporating a Ti/Au metallization, conventional photolithography, and an Au electroplating process to a thickness of 1 μm. The finger metallization is then used as mask for KOH etching of the PDB layer sequence down to the n^+ diffusion layer (see Fig. 1). Finally the lower ohmic contact is formed using a Ti/Au lift-off process and subsequent electroplating.

Fig. 2 shows a scanning electron micrograph of a coplanar PDB diode. The parameters of the diode, a C0681, are as follows: p^+ acceptor density, $6.5 \cdot 10^{11}$ cm^{-2}; undoped region width, 100 nm; active diode area, 36 μm^2. A photograph of the nearly symmetric $I-V$ characteristic is shown in Fig. 3. Diode dc parameters are obtained from computer-aided $I-V$ measurements and a fitting procedure to the thermionic emission equation. A series resistance of 20 Ω is determined. The barrier height is found to be 0.38 V, and the ideality factor is about 2.6 (the minimum theoretical value for a symmetric PDB diode being 2). The total capacitance at 10 MHz is 100 fF; the theoretical junction capacitance at 0 V is 18 fF.

III. Circuit Description

Fig. 4 shows the basic layout of the subharmonic pumped finline mixer. The structure is printed on a glass-microfiber reinforced PTFE (R/T-Duroid 5880, Rogers Corp.) of 127 μm thickness with a dielectric constant of 2.23. The subharmonic LO power is fed in via an E-band waveguide port and a tapered transition line. The RF signal enters from the left, passing through a D-band waveguide (below cutoff for the LO signal) and a matching discontinuity. It is reactively terminated by a band-stop placed half a wavelength behind the PDB diode. The microstrip high–low impedance filter connected to a 50 Ω stripline is designed to transmit the IF signal and to reject LO and RF frequencies, respectively. The diode chip as described before adheres to the metallization upside down ("flip-chip" mounting) crossing the 80 μm slot. The complete substrate is mounted in a combined WR12/WR7 waveguide housing; the IF is taken out through a K connector.

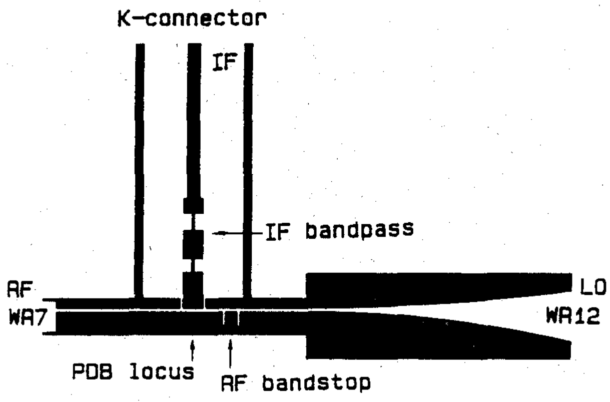

Fig. 4. Basic layout of the finline subharmonic pumped mixer.

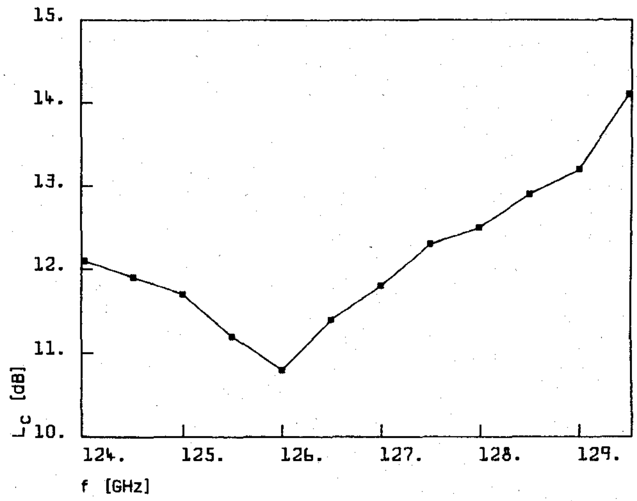

Fig. 5. Conversion loss versus RF frequency. $f_{LO} = 63$ GHz, $P_{LO} = 9$ dBm.

IV. Mixer Performance

The return loss of the RF input is measured to be better than 8 dB in the investigated frequency range (124 to 129 GHz), whereas the LO return loss is about 15 dB (63 GHz). In Fig. 5 the conversion loss, L_c, is plotted as a function of the RF frequency (LO frequency is fixed at 63 GHz, pump power is 9 dBm). The typical result for L_c across the band from 124 to 129 GHz is about 12 dB; a minimum value of 10.8 dB is observed close to 126 GHz. Note that the increase of L_c with increasing IF frequency is due to the narrow-band impedance transformation at the RF input of the mixer. Wide-band measurements from 106 to 145 GHz ($f_{LO} = 63$ GHz) result in a conversion loss below 20 dB. Further evaluation of the PDB subharmonically pumped mixer will continue with improvements in RF matching to increase the bandwidth and in MBE processing to reduce series resistances and junction capacitances. A conversion loss comparable to that of the best fundamental balanced mixers at D-band frequencies might be the result.

V. Conclusion

A subharmonically pumped finline mixer applying a silicon planar doped barrier diode has been developed for D-band frequencies. Excellent mixing properties (minimum conversion loss of 10.8 dB) favor this mixer configuration for application in low-cost receivers operating at those RF bands (above 120 GHz) where fundamental low-noise, solid-state oscillators are not currently available. A fully monolithic integration (MMIC) on highly insulating silicon substrate employing an IMPATT diode as local oscillator [7] will be realized in the future.

Acknowledgment

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A Simple Method for Characterizing Planar Transmission Line Discontinuities on Dissipative Substrates

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Abstract—**A simple, least-squares sum curve fitting technique is presented which accurately models surface currents on planar transmission lines. This approach is useful for characterizing discontinuities occurring in MIC's fabricated on dissipative substrates. Numerical results for the microstrip open end on a lossy GaAs substrate are given.**

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I. Introduction

Costly design cycles which occur during the fabrication of microwave MIC's serve to illustrate the need for accurate characterization of passive planar transmission structures. In particular, microstrip discontinuities occurring in shielded substrate geometries have received a great deal of recent attention and several different full-wave methods have been proposed [1]–[5]. In these works, the microstrip circuitry is located on either an assumed lossless or a low-loss substrate and device scattering parameters are computed with relative ease.

When appreciable substrate losses are present, it is very difficult to calculate the complex propagation constant from the current distribution on the input port transmission line. In addition, the corresponding standing wave ratio is not a constant and, consequently, the approach utilized in [1] is impractical. The mode-matching technique [2] requires knowledge of several higher order microstrip mode propagation constants. These parameters are essentially computed by finding the roots of an intricate complex function—a potentially troublesome task when a lossy substrate is being considered. The time-domain finite difference approach [3] and related methods are applicable to the problem being addressed in this paper but can be cumbersome to work with. The analyses presented in [4] and [5] are also applicable to dissipative substrate structures. However, the technique discussed in [4] yields results only for the overall circuit and does not specifically consider the scattering characteristics of the dominant microstrip mode. Application of the method in [5] requires a separate algorithm to calculate the dispersion parameters of the input port microstrip lines. Clearly, disadvantages are evident in all of the above analyses.

Microwave and millimeter-wave integrated circuits fabricated on semiconducting substrates are compatible with optical and voltage control technologies. Because of this and other applications [6], substrate losses cannot, in general, be ignored when analyzing passive components. Thus, a simple, new procedure for finding scattering parameters under these conditions, which suffers from none of the drawbacks discussed, is of interest.

In this paper, a simple technique for characterizing microstrip discontinuities on lossy substrates is given. Numerical results (S_{11}) for the microstrip open end on a GaAs substrate are given versus substrate thickness for various values of substrate conductivity and operating frequency.

II. Theory

The geometry of a shielded microstrip open end is shown in Fig. 1(a). The method presented here to characterize the microstrip open end may be used in conjunction with any full-wave method which yields the surface current distribution on the metallized region [1], [4], [5]. The space-domain integral equation approach has been experimentally verified [7] and is utilized in this paper. The present formulation is virtually identical to that in [1] except the Green's function is derived using the technique given in [8]. Other details pertaining to the method may be found in [1]. The current distribution on the microstrip line is obtained from the well-known relation

$$[I]=[Z]^{-1}[V]. \quad (1)$$

In the region on the strip between the discontinuity reference plane and the excitation point (say, a distance of $\lambda_g/4$ from each) an ideal transmission line current exists as long as the operating frequency is below the cutoff frequency of the shielding structure. This is illustrated in Fig. 1(b). Note that this criterion is satisfied for all results given in this paper.