Millimeter Wave Tripler Evaluation of a Metal/2-DEG Schottky Diode Varactor

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***Abstract*—A new Schottky diode, based on a contact at the edge of a 2-dimensional electron gas (2-DEG) is investigated for use as a multiplier element in the millimeter and submillimeter wavelength regions. As a negative voltage is applied to the Schottky contact, the depletion layer between the Schottky contact and the 2-DEG expands and the junction capacitance decreases, resulting in a non-linear reactance. Device results are presented which demonstrate low series resistance, large capacitance modulation, and significantly higher tripler efficiency (75–225 GHz) than previously reported multiplier results of this type of structure.**

I. Introduction

SCHOTTKY barrier varactor diodes are used as frequency multiplier elements for local oscillator sources in millimeter and submillimeter wavelength receivers. These systems are used for a variety of applications including radio astronomy, atmospheric studies and plasma diagnostics. Until recently, such receiver systems relied on whisker-contacted varactor diodes which were optimized together with the multiplier circuit (typically a waveguide circuit). Increasing interest in space-based applications has motivated the development of new solid state LO systems using planar diode technology. These systems are more rugged and more easily space qualifiable than their whisker-contacted counterparts. Recent multiplier results [1] have demonstrated that planar varactor diodes and multiplier circuits can be co-designed to yield comparable performance to the whisker-contacted versions.

As the operating frequencies of space-based applications increase to 1 THz and above, a greater premium is placed on achieving high multiplier efficiency, since each additional stage of the multiplier chain places increasing power requirements on the fundamental oscillator (typically a Gunn oscillator). While the GaAs varactor diode is a promising candidate for THz LO applications, several novel devices, including the delta-doped anti-series pair [2]–[4], the Quantum Barrier Varactor [5], [6], and the metal/2-DEG (2-dimensional electron gas) diode [7], [8], are also of interest since these devices may offer advantages in power, efficiency, or cutoff frequency compared with the GaAs device. The metal/2-DEG device is inherently planar and is monolithically integratible with HEMT transistors and optoelectronic components. This paper describes the recent progress on the metal/2-DEG diode for millimeter wavelength LO applications.

Manuscript received August 16, 1994. This work was supported by the National Science Foundation under Grant ECS-9113123 and by the Office of Naval Research under Grant N00014 90-J-4006.

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IEEE Log Number 9408309.

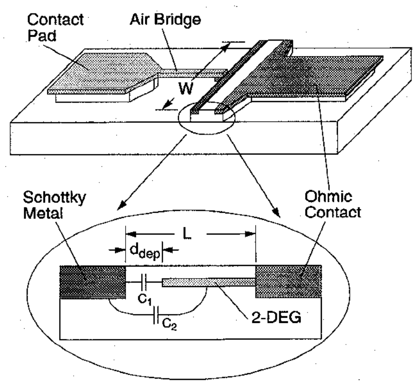

Fig. 1. Diagram of 100 μm width metal/2-DEG varactor device. Inset shows detailed cross section of junction area. L is the device length. W is the device width. d_{dep} is the length of the depleted 2 DEG. C_1 and C_2 represent schematically the components of the total junction capacitance, where C_1 is the capacitance analogous to a parallel plate capacitor, and C_2 is the capacitance analogous to two coplanar strips.

II. Diode Description and Fabrication

The heterodimensional (3d-2d) metal/2-DEG diode is illustrated in Fig. 1. The 2-dimensional electron gas forms in the InGaAs layer of an AlGaAs/InGaAs heterostructure. A Schottky contact is made by electroplating metal onto the edge of the 2-DEG. Associated with the Schottky barrier is a 2-dimensional depletion region whose length varies with applied bias, resulting in a voltage dependent junction capacitance. At high reverse biases the depletion length is long with respect to the height of the Schottky contact, yielding a capacitor geometry analogous to two coplanar parallel strips. At low biases, the depletion length is comparable to the thickness of the 2-DEG. Under these conditions, an additional parallel plate capacitance between the edge of the 2-DEG and the Schottky metal becomes significant. A detailed analysis of the heterodimensional metal/2-DEG junction capacitance was described previously [9].

The metal/2-DEG diodes were fabricated on a double delta-doped pseudomorphic $Al_{0.23}Ga_{0.77}As/In_{0.2}Ga_{0.8}As$ structure, grown by molecular beam epitaxy. The substrate was semi-insulating GaAs on which was grown the following layers: 500-nm undoped GaAs buffer, a 0.8 $\times$ 10^{12} cm^{-2} Si doping plane, 30-nm undoped AlGaAs, 12-nm undoped InGaAs, 3-nm undoped AlGaAs, a 3.6 $\times$ 10^{12} cm^{-2} Si doping plane, 30-nm AlGaAs doped (Si) to 5.0 $\times$ 10^{17} cm^{-3}, and 6-nm of GaAs doped (Si) to 4.0 $\times$ 10^{18} cm^{-3}. Van de Pauw measurements made immediately after growth indicated an electron sheet density of 2.7 $\times$ 10^{12} cm^{-2} and electron mobility of 5800 cm^2/ Vs at 295 K. Ni/Ge/Au/Ag/Au ohmic contacts were deposited by evaporation and were subsequently alloyed at 470°C, yielding contact resistivities (r_{sc}) of about 0.2 Ωmm. To form the Schottky contact, a trench was etched through the 2-DEG layer and Pt and Au metals were electroplated into the trench. The resulting 2-DEG channel length, between the Schottky and ohmic metal, was approximately 0.5 μm and the channel width was 100 μm. Next, the interconnect metal was evaporated, after which the epitaxial layers outside the channel were removed using a wet etch. This etch removes the material beneath the air bridge metal (Fig. 1), resulting in very low parasitic capacitance [10]. Finally, the wafer was diced and lapped into discrete chips with dimensions 125 μm × 200 μm, with a thickness of 40 μm. This size allows the devices to be individually soldered into the millimeter wave half-height output waveguide of the multiplier block.

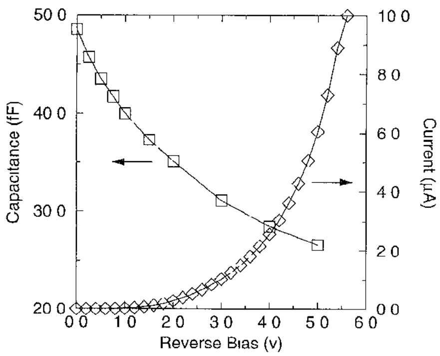

Fig. 2. Capacitance and leakage current versus reverse bias for a 100 μm width metal/2-DEG varactor. Squares—capacitance; diamonds—leakage current.

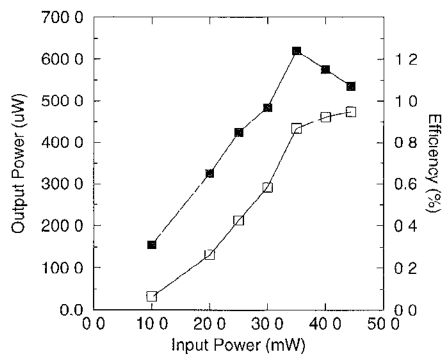

Fig. 3. Measured output power and corresponding efficiency of 75 to 225 GHz tripler block using a metal/2-DEG diode as the varactor element Open squares—device output power; filled squares—device efficiency.

III. Device Evaluation

The current-voltage characteristics were measured at room temperature and are shown in Fig. 2. A theoretical fit for the measured forward $I - V$ data was obtained using the thermionic emission diode equation:

$$I = I_{sat} \exp\left[\frac{q(V - IR_s)}{\eta k_B T}\right]$$

where V is the applied voltage, I is the current, R_s is the series resistance, and η is the diode ideality factor. The fitting parameters were $\eta = 1.33$, $I_{sat} = 9.68$ pA, and $R_s = 8$ Ω. The series resistance is equal to the sum of the undepleted 2-DEG channel resistance, $R_{channel}$, the ohmic contact resistance, R_{ohmic}, and the anode metal resistance R_{metal}. The channel resistance and the ohmic contact resistance were each estimated to be about 2Ω, leaving about 4Ω which we attribute primarily to resistance in the Schottky metal. This relatively large metal resistance may be reduced by increasing the electroplated anode metal thickness. The reverse $I - V$ and $C - V$ are shown in Fig. 2. The capacitance varies from 47 fF at zero bias to 27 fF at −5.5 V, where the leakage current exceeded 10 μa. At this voltage, the 2-DEG channel is fully depleted, so that the remaining 27 fF represents anode-metal-to-ohmic-metal shunt capacitance. It may be possible to reactively tune most or all of the shunt capacitance through the air bridge inductance or other circuit elements. This will require longer air bridges than those in the present design.

These results show a significant improvement in series resistance over prototype versions of the device reported in [8]. This improvement was achieved by several changes in the device, most significantly the reduction in channel length from 2.5 μm in the previous device to approximately 0.5 μm. Also, the channel conductivity was improved by using two doping planes to achieve higher electron sheet density, and a new ohmic contact yielded lower contact resistivity. These improvements resulted in a reduction in R_s from 19.9 Ω to 8 Ω. The previous devices had a capacitance which varied from 37 fF to 12 fF.

The metal/2-DEG varactor diode was evaluated in a waveguide circuit as a frequency tripler to 225 GHz. A mechanically tunable Gunn oscillator was used to provide the input power from 70 to 84 GHz. This input power was passed through a variable attenuator, and could then be directed either to a power meter (to measure input power), a notch filter (to measure frequency), or the tripler block. The tripler block was originally designed for use with whisker-contacted Schottky varactor diodes, but was modified so that a planar chip could be soldered across the output waveguide [11]. The output power was chopped at 35 Hz and directed into a Thomas Keating millimeter/submillimeter-wave power meter [12]. The output of the Keating meter was measured with a lock-in amplifier. The output power at 225 GHz and the tripler efficiency versus input power are shown in Fig. 3. At each data point, the tuning and DC bias voltage were adjusted for maximum output power. A maximum efficiency of 1.24% was achieved at 35 mW input. This represents a 150% improvement over previous results [8]. By comparison, the best efficiency from a planar GaAs Schottky diode in this tripler at these frequencies was about 3.2% [13]. This result used a UVA SC6T2 diode with $R_s = 6$ Ω $C_{max} = 30$ fF, and $C_{min} = 8$ fF. We attribute the lower efficiency of the present device compared with the GaAs device to the large parasitic capacitance which has not been tuned by sufficient interconnect inductance.

IV. Conclusion

A novel varactor device utilizing a metal/2-DEG junction has been investigated. Improved multiplier devices were designed and fabricated and were tested at DC and at 225 GHz. The capacitance varied from 47 fF at zero bias to 27 fF at −5.5 V, and the series resistance was 8 Ω at room temperature. A frequency tripler conversion efficiency of 1.24% was measured at 225 GHz. This result is significant, as it offers proof that this novel device is indeed capable of operation at millimeter wavelengths. It suggests that with further optimization of the device and circuit, the metal/2-DEG diode may be useful as a frequency multiplier element well into the submillimeter wavelength region.

ACKNOWLEDGMENT

The authors thank T. Hierl and W. Weisbecker of Quantum Epitaxial Designs, Inc. for providing the MBE material.

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