A W-Band Medium Power Multi-Stack Quantum Barrier Varactor Frequency Tripler

Ali Rahal, R. G. Bosisio, C. Rogers, J. Ovey, M. Sawan, and M. Missous

***Abstract*—Conventional multi-stack quantum barrier varactor (MSQBV) diodes on GaAs suffer from leaky barriers and low breakdown voltage, which limits their performance in high-power applications. Using a lattice-matched InGaAs/InAlAs/InGaAs barriers on InP we have grown a new 10-stack device. Measurement results are presented that demonstrate low series resistance, large capacitance modulation, and significantly higher breakdown voltage than previously reported devices. The power capability of this new device has been investigated by simulations and measurements. An experiment in a waveguide tripler circuit shows a 19.6 dBm output power at 93 GHz. This is the highest output power reported from a single QBV device at *W*-band.**

I. Introduction

FREQUENCY multipliers have been used as a local source in different millimeter and submillimeter wave heterodyne receivers. Actually, such sources are demanded for application in PCN and IVHS systems where the efficiency and power output of the solid state fundamental sources, such as Gunn diodes, are too low [1]. Recently, a new class of varactor diodes having symmetrical even capacitance-voltage (C-V) and odd current-voltage (I-V) characteristics such as QBV, back-to-back barrier-N-N$^+$ (bbBNN$^+$) have been introduced [2], [3]. This new class of varactors is able to generate, with high efficiency, odd harmonics at millimeter and sub-millimeter wave frequencies with no bias requirement. Compared to a conventional Shottcky barrier varactor tripler, the design of an MSQBV tripler is greatly simplified since no Idler nor bias circuits are needed. Although a 100% conversion efficiency is theoretically possible from an ideal nonlinear capacitor [4], the actual efficiency in real circuits is limited by the losses in the device and embedding circuit. The earlier reported QBV suffered from leaky barriers and relatively high series resistance, resulting in an output power saturation at low input power levels. In order to overcome this limitation a high breakdown voltage device with low leakage current is needed. The heterostructure of the QBV offers the possibility of stacking a number of barriers, so as to elevate the operating voltage of the device [5]. A recent attempt to realize such a multi-stack device on GaAs resulted in a device whose C-V characteristic cannot be measured beyond 2 V because of the excessive conduction current in the barrier [6]. In this work, we present a 10-stack QBV on InP with 22 V breakdown voltage and low series resistance suitable for medium power applications at millimeter wavelengths. An accurate nonlinear data-table-based model is introduced for the first time on such a device. Both simulations and measurements, demonstrate improved performance at millimeter-wave frequencies and good agreement in predicting power level and efficiency.

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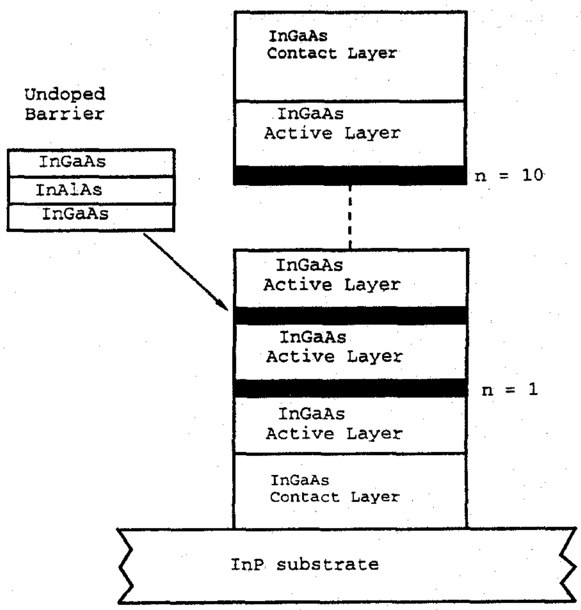

Fig. 1. The lattice matched MSQBV layer structure.

II. Device Description

In order to realize a high performance device, different barrier structures have been investigated. As a result, a barrier composed of InGaAs/InAlAs/InGaAs is chosen. The layout of the multi-stack quantum barrier varactor (MSQBV) is shown in Fig. 1. The material is grown by molecular beam epitaxy (MBE) on an n^+-InP substrate. A highly doped InGaAs layer is first grown on the substrate, followed by a sequence of InGaAs active layers and barriers. The barriers are made from InAlAs with a thin undoped layer of InGaAs on either side. All layers are lattice matched to InP. This material system gives a conduction band discontinuity of 0.53 V. A highly doped InGaAs layer completes the structure. Ohmic contacts were

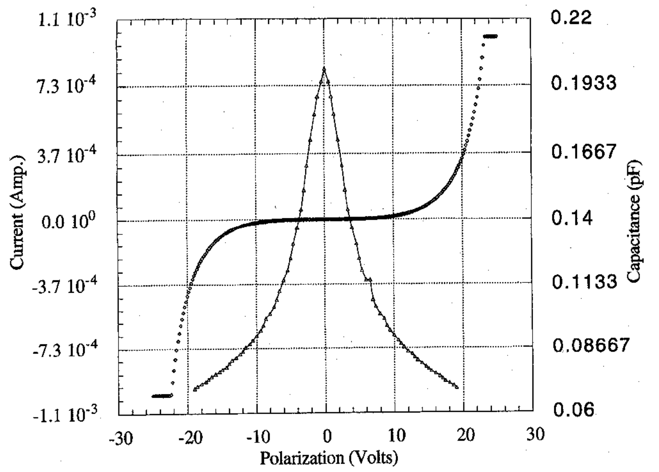

Fig. 2. Measured capacitance to voltage and current to voltage curves of the MSQBV. ○ Current; —△— Capacitance.

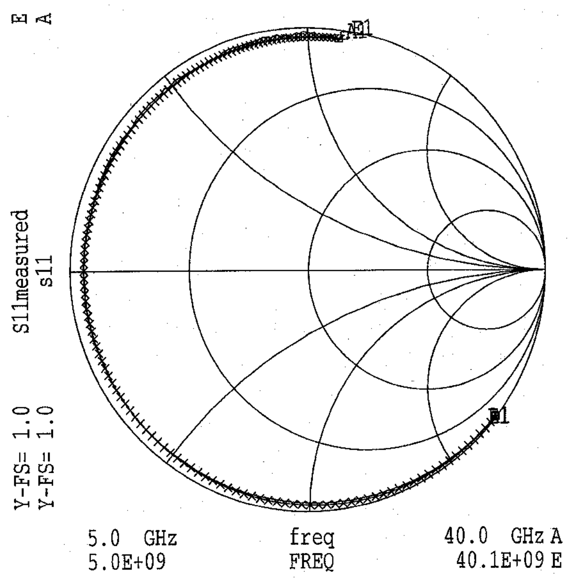

Fig. 3. Modeled and measured S_{11} parameter of the MSQBV diode form 5–40 GHz.

made to the highly doped InGaAs layers at each end of the epitaxial structure. The mesas were produced by wet etching.

III. Characterization and Modeling

In order to characterize the diode, a chip device is fixed in shunt on a special coplanar waveguide (CPW) mount. The fixtured diode is then mounted on a probing station and dc measurements are made using the HP 4155 A Semiconductor Parameter Analyzer. The resulting data shows a breakdown voltage of ±22 V for a conduction current of 1 mA. The current to voltage and capacitance to voltage characteristics are shown in Fig. 2. The S_{11} parameters were then measured from 5–40 GHz at different biases using an HP8510 Network Analyzer fully calibrated at the diode plane with the thru-reflect-line method (TRL). The resulting data is used to extract the C-V characteristic of the device. A table-based model built on spline interpolation functions is used to accurately represent the nonlinearity of the device. With this model, a very good fit at all bias points is obtained. In Fig. 3, measured and modeled results at one bias point are shown. The S_{11} measurements indicate a very small series resistance of 1.3 Ω. This low value explains the high conversion efficiency obtained in the operating device. A $C_{\max}/C_{\min}$ ratio of 2.85 was also obtained; this value ensures a good capacitance swing that leads to an efficient harmonic generation and high conversion efficiency [7]. Using the measured values of R_s, $C_{\max}$ and $C_{\min}$ we have calculate a dynamic cutoff frequency of 1.516 THz [3].

IV. Large Signal Simulations and Measurements

Large-signal simulations were performed using the Harmonic-Balance technique [8]. Fast convergence is realized using the table-based model. Input and output matching networks were optimized at the fundamental and the third harmonic respectively. The embedding impedances were set to open circuits at every alternate odd harmonic. Simulation and measurement results are shown in Fig. 4. Measurements have been done using a waveguide tripler mount and an

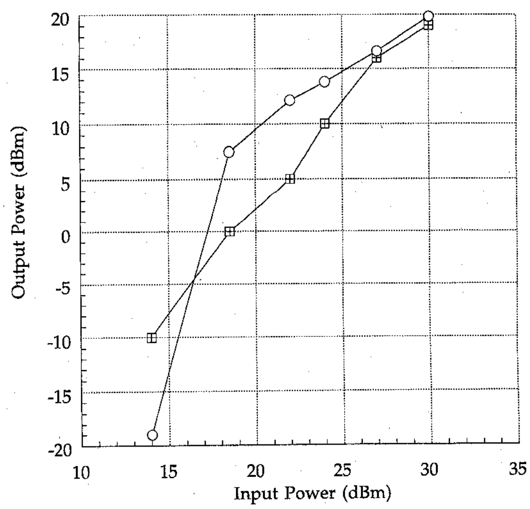

Fig. 4. Measured and simulated third harmonic output versus input power for the 93 GHz MSQBV frequency tripler. Load is optimized for the 30 dBm input level. —⊞— Measured; —○— Simulated.

output power of 19.6 dBm with corresponding 10% port to port efficiency was obtained, this result is consistent with the simulations when the losses in the input and output circuits are considered. Considering lossless matching circuits, a 25% conversion efficiency is calculated at the diode level. This improved efficiency is the direct result of the low leakage current and the low series resistance of this new device. Previous results on tripler reported using leaky InP varactors exhibit a saturation in the power transfer characteristic at low input driving levels. In contrast, simulation and measurements using the MS-QBV indicate a saturation free operation up to the breakdown voltage, this is consistent with the Manly-Rowe relation [4] predicting 100% conversion efficiency for reactive multiplication. It is to be noted that the simulated RF peak current of 648 mA is found to be smaller then the 1.5 A saturation current calculated assuming a $2.5 \cdot 10^5$ m/s carrier velocity in InP, which confirms the saturation free operation [9].

V. Conclusion

A high power, high efficiency MS-QBV on InP is reported. Using lattice-matched barriers, a 10-stack heterostructure is achieved. On wafer measurements show that this device has a very low series resistance of 1.2 Ω and a breakdown voltage of 22 V. Output power of 19.6 dBm at 93 GHz from a single device have been realized. This power level is suitable for many IVHS and PCN applications.

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