Novel Varactor Diode Structures for Improved Power Performance†

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ABSTRACT

This paper describes two novel varactor structures to improve the power performance of multiplier sources. The first structure is similar to the conventional Schottky diode varactor with the addition of a wider-bandgap semiconductor layer at the Schottky contact. The wider bandgap material presents a larger barrier to electron flow in forward bias and a larger breakdown voltage in reverse bias. The second device structure, the back-to-back Schottky Diode Varactor (bbSDV), is a lateral current flow device with a symmetric C-V characteristic. The structure is similar to two Schottky diode varactors connected cathode-to-cathode except the ohmic contacts are eliminated and the two Schottky barrier diodes share the same depletion region. Eliminating the contacts and some of the low-doped depletion material should reduce the series resistance. A bbSDV has been fabricated with less than 0.4 A/cm^2 leakage current and a C_{max}/C_{min} ratio greater than 3 for a ±20V voltage swing.

I. Introduction

Solid state power sources in the 100-3000 GHz frequency range are essential in heterodyne receivers used for radio astronomy and remote sensing. To obtain high spectral resolution in the millimeter and sub-millimeter wave regime, heterodyne receivers are implemented to convert an incoming signal to a much lower intermediate frequency for amplification. These systems require a mixing element and a local oscillator power source

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near the frequency of interest. Solid state fundamental oscillator sources are not available in the sub-millimeter wave range, so harmonic multipliers utilizing varactor diodes become a critical component. This paper will present two novel varactor structures to improve the power performance of multiplier sources. The first structure is similar to the conventional Schottky diode varactor but utilizes a wider-bandgap semiconductor layer at the Schottky contact. The second device structure, the back-to-back Schottky diode varactor (bbSDV), is a lateral current flow device with a symmetric C-V characteristic.

II. AlGaAs Barrier Structure

All varactors depend on a nonlinear capacitance-voltage relation for harmonic generation and some type of barrier to real current flow. The most common is the reverse biased Schottky diode. This diode consists of a Schottky contact on top of a doped semiconductor with a back ohmic contact. The metal-semiconductor junction forms a barrier to electron flow while the semiconductor depletion region forms a capacitor with the well known inverse-square-root voltage dependence. A large barrier height is desired to increase the voltage swing and reduce the leakage current.

The limitations on conventional varactor performance include (1) the capacitance ratio, (2) breakdown voltage and forward conduction, (3) velocity saturation [1], and (4) displacement current in the neutral region. With doping, a trade-off is made between items (1)&(2) and (3)&(4). In other words, a lower doping improves the capacitance ratio and voltage swing and a higher doping reduces the effects of velocity saturation and displacement current in the neutral region.

A variation of the conventional varactor described above is one with a heterostructure of two materials with different bandgaps. One such arrangement, as shown in figure 1, places a larger bandgap material (barrier region), AlGaAs, between the Schottky contact metal and the lower bandgap material (deletion region), GaAs. The advantages of this structure include (1) an additional degree of freedom in the device design, (2) a higher breakdown voltages in reverse bias, and (3) a larger barrier to electron flow in the forward direction. Potential problems include poor transport in the barrier AlGaAs layer and possible Γ-X transport which would lower the effective barrier height.

Figure 2 shows the calculated breakdown voltage vs. doping for a uniform AlGaAs structure of four different Al-fractions. From Sze [2], breakdown is the point where

$$1 = \int_0^w \alpha_n(\varepsilon)\, dx$$

with the ionization data from Chau [3]. As can be seen for a reasonable doping, an increase in the Al-fraction results in a significant increase in breakdown voltage. In figure 3, the heterostructure breakdown voltage vs. AlGaAs layer width is calculated for three doping levels with three Al-fraction levels each. At a given AlGaAs width, a substantial increase in breakdown voltage is possible.

An AlGaAs/GaAs heterostructure varactor has been fabricated and the I-V characteristics are shown in figure 4. The structure is a 300Å, 3.0×10^{16} cm^{-3} N-doped $Al_{0.3}Ga_{0.7}As$ barrier layer on a 6000Å, 3.0×10^{16} cm^{-3} N-doped GaAs depletion layer with an N+ doped GaAs layer. For comparison, a 5700Å, 3.0×10^{16} cm^{-3} N-doped GaAs depletion layer with an N+ doped GaAs layer structure is also shown. As can be seen, the heterostructure device has approximately a 0.5V larger turn on voltage and nearly a 3V greater breakdown voltage. The increase in the voltage swing should increase the power capability.

The added flexibility of a barrier layer can be used to increase the voltage swing, as shown above. However, by both adding the barrier layer and increasing the doping so as to keep the same breakdown voltage, the efficiency of the varactor can be increased. A performance analysis has been completed on a GaAs varactor doubler operating with an input frequency of 80GHz. The analysis, detailed in East *et. al.* [4], includes effects of forward conduction currents, velocity saturation, displacement currents in the neutral region, and breakdown currents. Figure 5 shows the calculated efficiency vs. the input power for three conditions. The first condition for a 20V breakdown voltage and $3x10^{16}$ cm^{-3} doping represents a GaAs Varactor. The second represents a same doping but greater breakdown voltage as an AlGaAs capped sample. For the third condition, 20V breakdown and $4x10^{16}$ cm^{-3} doping, the addition breakdown voltage is exchanged for an increase in doping. As can be seen, by increasing the doping, the peak efficiency shifts from 42% to over 53%. The corresponding peak power levels can be seen in figure 6.

III. Symmetrical Structure

Symmetrical structure varactor diodes provide multiplication by 3 with a simpler circuit and require no bias. Some current approaches include the single barrier varactor (SBV) [5] and the back-to-back barrier-N-layer-N+ varactor (bbBNN) [6]. The proposed structure is a back-to-back Schottky diode varactor (bbSDV).

The bbSDV structure has a rectangular mesa with Schottky contacts on two opposite edges. The Schottky metal extends on each of the sides to form contact pads. Unlike most varactors where the current flow is normal to the epitaxial layers, this structure utilizes a lateral current flow. A drawing of the device is shown in figure 7. In figure 8, micrographs of a back-to-back Schottky diode varactor is shown with a cross-sectional area of 25 μm^2 and mesa length of 4µm.

Electrically, the bbSDV can best be described as two back-to-back Schottky diodes that share a single depletion region. Under zero bias, each junction has a small depletion region and thus the capacitance is large. When biased, most of the voltage-drop will be across the reverse biased junction while the other junction will change only slightly.

A simple model of this device at low to moderate voltages is a capacitance, resembling the series combination of the depletion capacitance at each Schottky, in series with a series resistance corresponding to the undepleted semiconductor between the two depletion regions. Under zero bias, the two capacitors are just the junction capacitances in series with the series resistance. When a bias is applied, one of the depletion regions expands causing an associated decrease in both the junction and total capacitance. Since the same occurs with the other junction in the opposite bias, the C-V characteristics are symmetrical about the zero bias point. The change in capacitance with bias requires a leakage current flow at the forward bias junction, because charge accumulation is not supported in this structure [7] [8]. This will limit the frequency response of the device.

A barrier layer at the Schottky contact interface can provide a potential solution to the leakage current requirement. Such a barrier has been demonstrated with the increased turn on voltage of figure 10 in which an Al_2O_3 barrier layer was placed at the interface of a single Schottky diode structure. The semiconductor material structure consisted of a 300Å $1x10^{18}$ cm^{-3} N-doped GaAs epitaxial layer on an N+ doped GaAs ohmic layer.

A bbSDV without a barrier layer has been fabricated with the following properties. A GaAs semiconductor N-type epitaxial layer of doping $4.3x10^{16}$ cm^{-3} and thickness of 1µm on a semi-insulating GaAs substrate was used in the device. The metal contacts were formed with a Ti/Au deposition. The I-V characteristic, as shown in figure 9, displays that for a large voltage swing, there is less than 1 µA of leakage current for a 75 μm^2 cross sectional area. This corresponds to 1.3 A cm^{-3} of leakage current for a ±20V swing. A C_{max}/C_{min} ratio of greater than 3 is also in the C-V characteristics of figure 9.

The bbSDV has many advantages over other varactor devices. The fabrication process requires only two lithographic steps and no back side processing except substrate removal. This simplifies fabrication and hence increases throughput and device to device uniformity. A second advantage is the good control of capacitance via the contact area. In this structure, the contact area can be specified much more accurately than in a vertical structure since a small height dimension is already accurately defined. The third advantage is a high voltage swing with low leakage current as the Schottky diode varactor. This larger voltage swing corresponds to a larger power handling capability. The bbSDV has the properties of two Schottky diode varactors connected cathode to cathode, except for the series resistance since the depletion region is shared.

IV. Conclusions

Two novel structures to improve the power performance of multiplier sources were presented. The first structure, very similar to a conventional Schottky diode varactor, utilized an AlGaAs barrier layer to provide an additional degree of freedom, a design trade off between the breakdown voltage and doping. Also the barrier increased the turn on voltage. Through a performance analysis, it was shown that doping dominates the efficiency.

The second structure presented is the bbSDV. The advantages of this device is the good control of capacitance, few fabrication steps, lower leakage current for a large voltage swing, and a symmetric C-V characteristic for 3rd harmonic multiplication. A potential problem exist at RF because charge accumulation is not supported. However, a similar structure is proposed with barriers that would circumvent such a problem.

List of Figures

References

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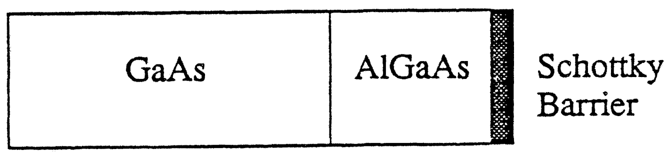


Figure 1

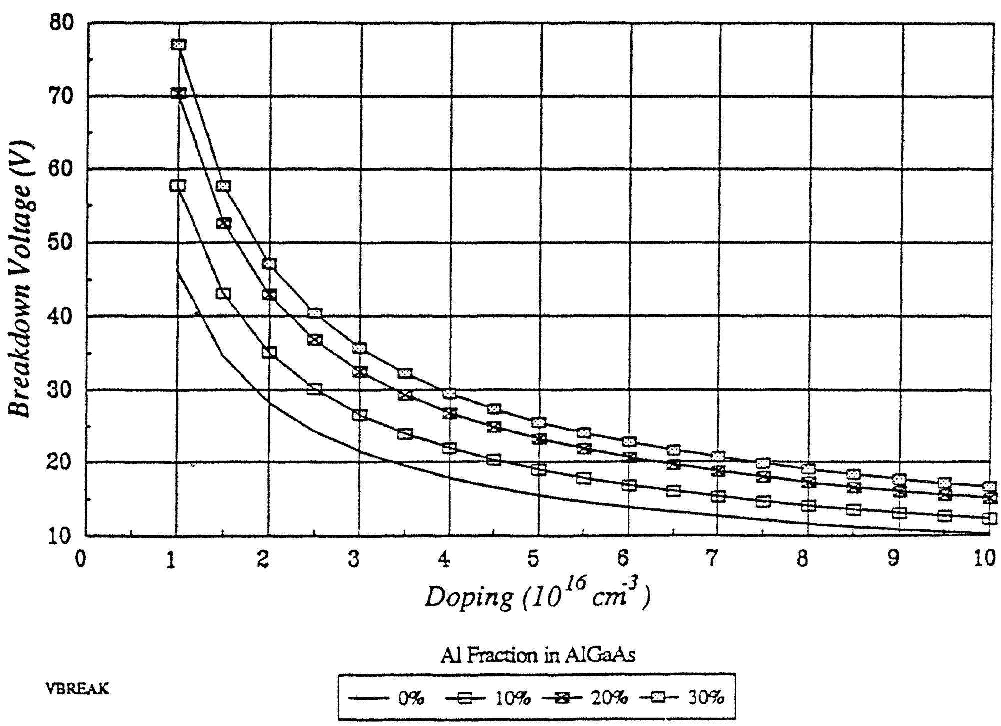


Figure 2

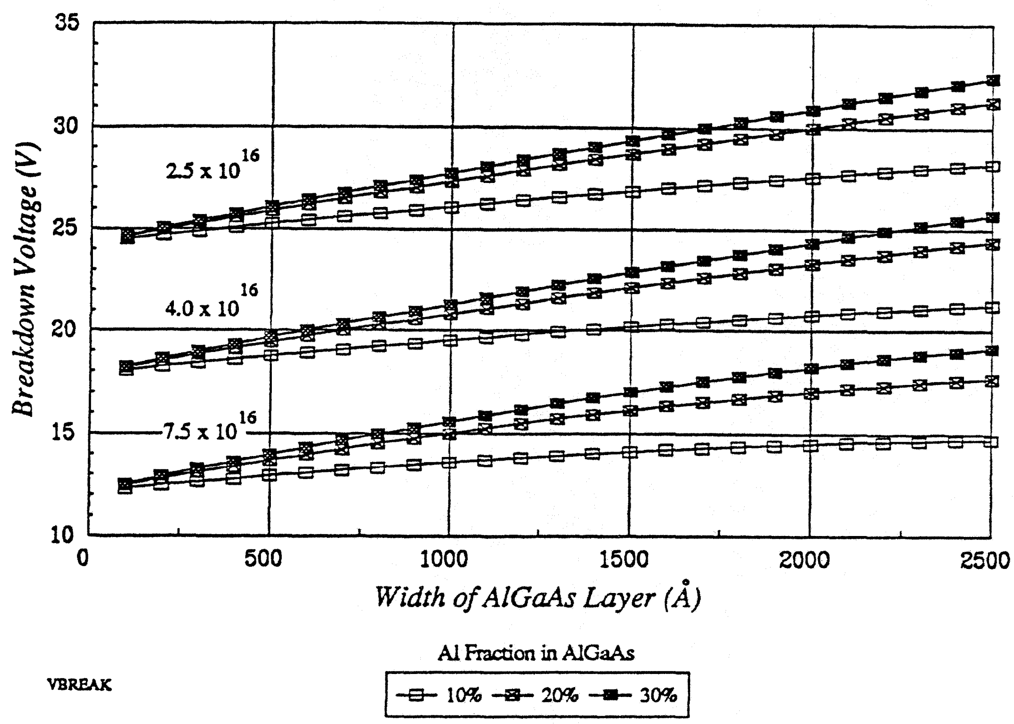


Figure 3

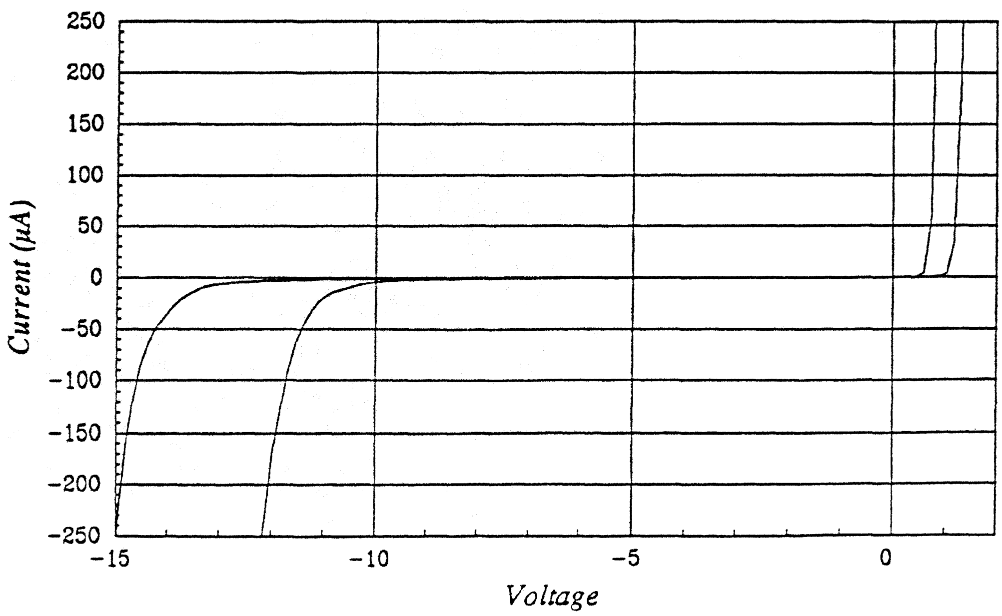


Figure 4

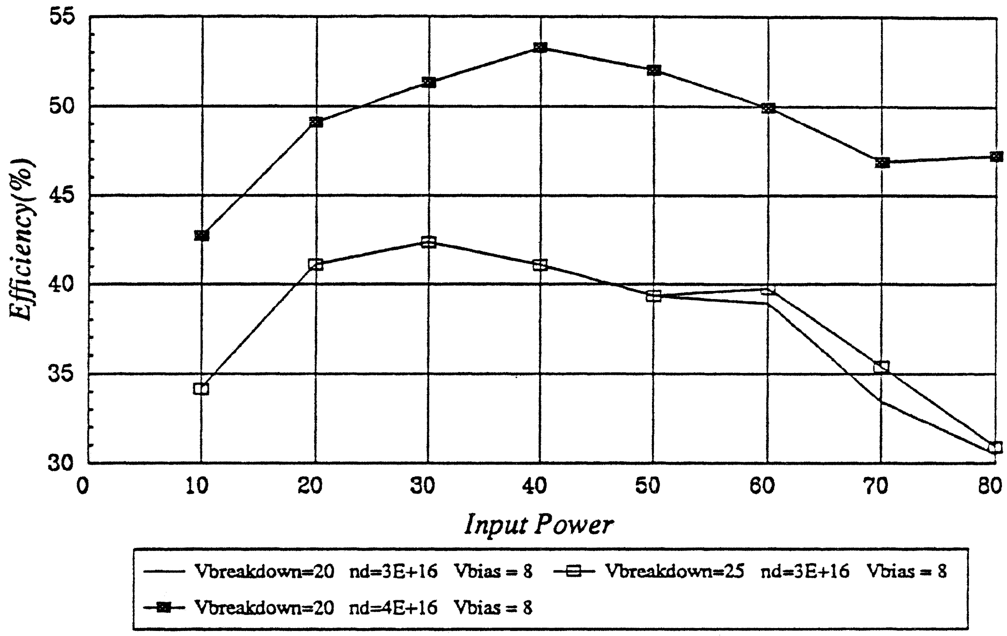


Figure 5

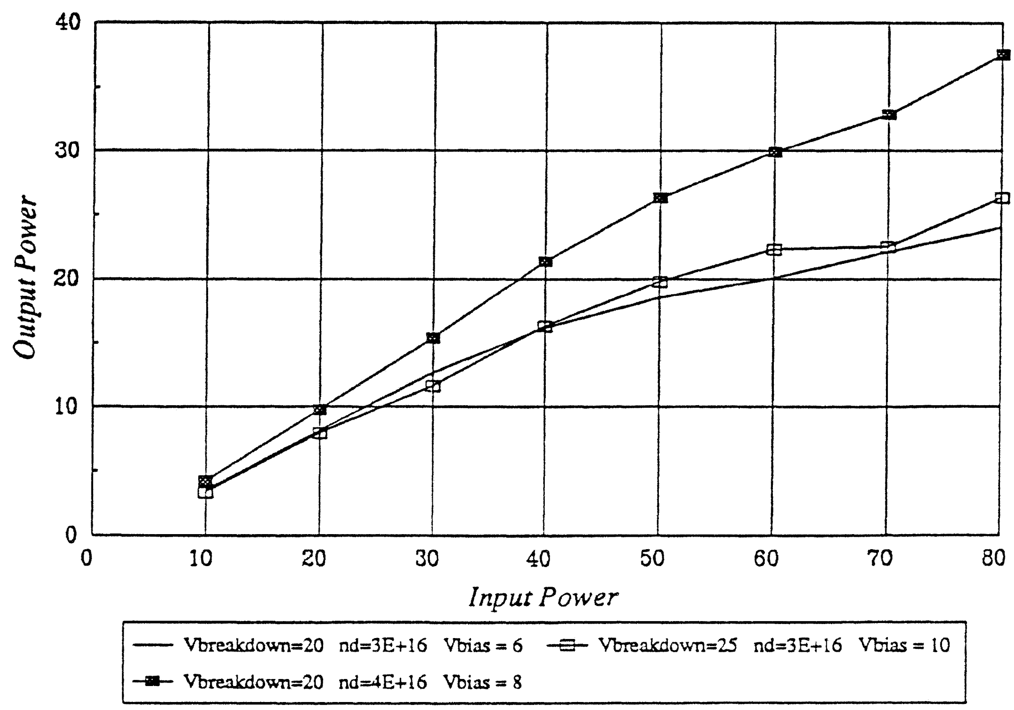


Figure 6

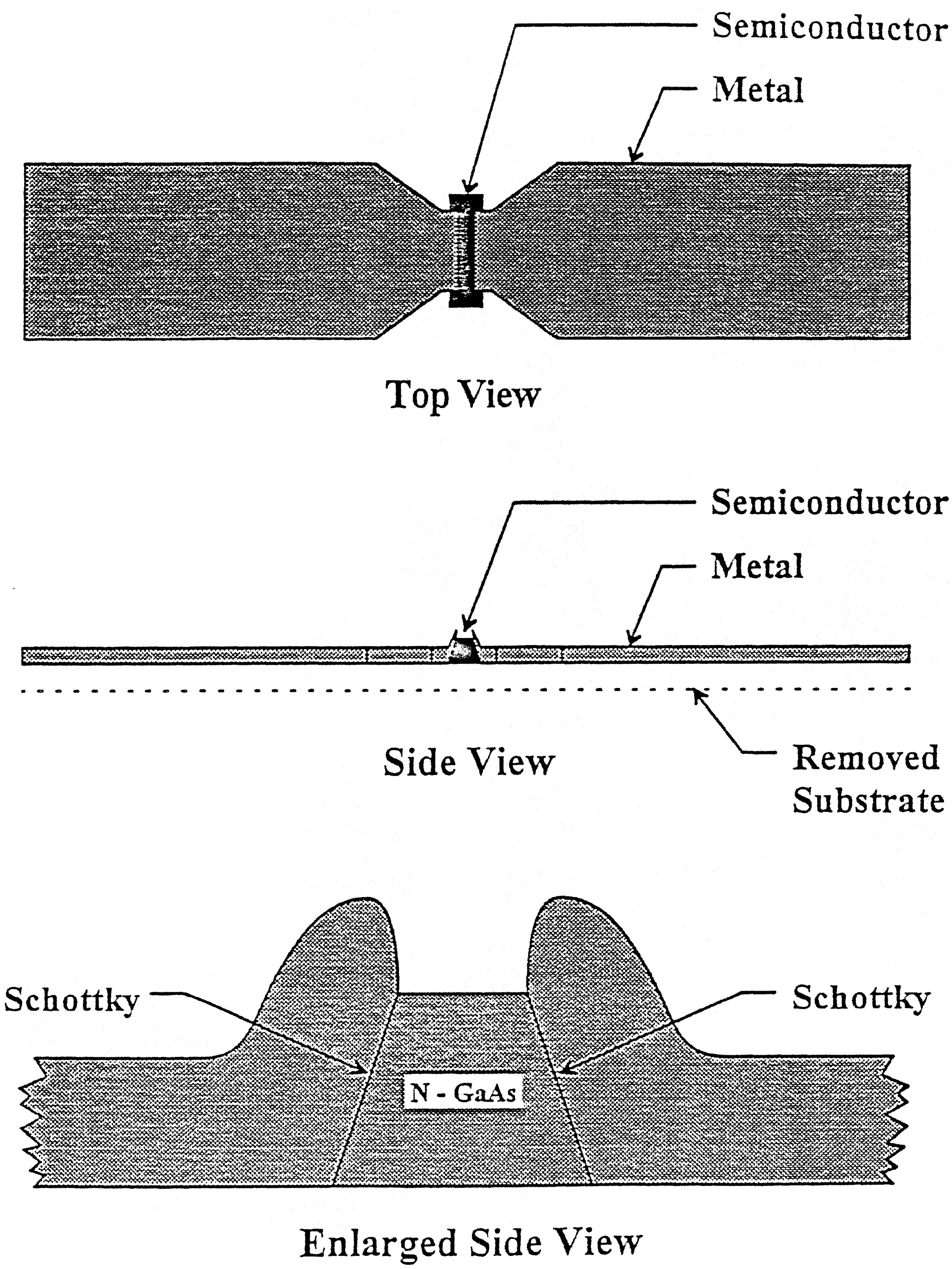

Semiconductor
Metal
Top View
Semiconductor
Metal
Side View
Removed Substrate
Schottky
Schottky
N - GaAs
Enlarged Side View

Figure 7

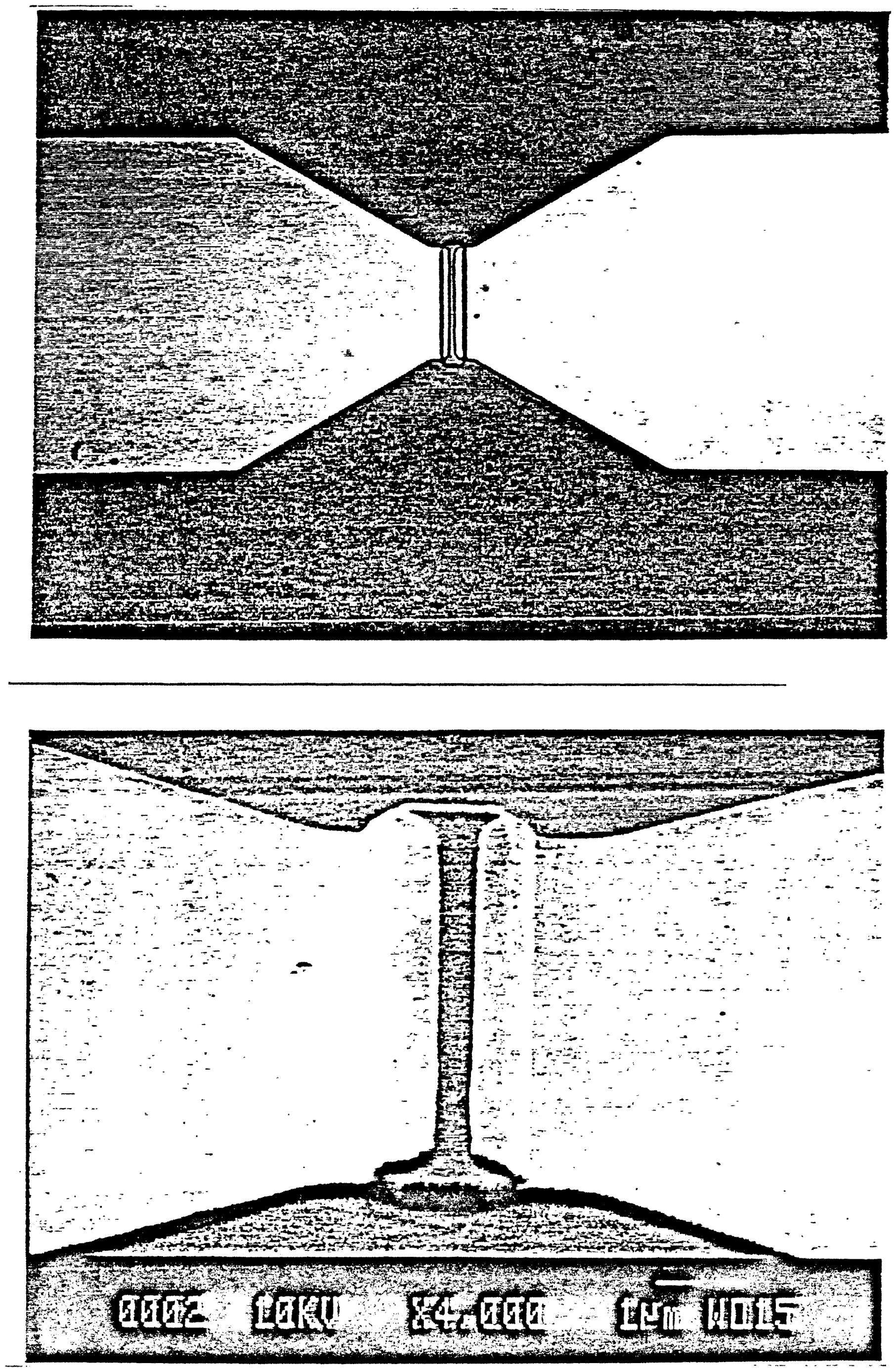
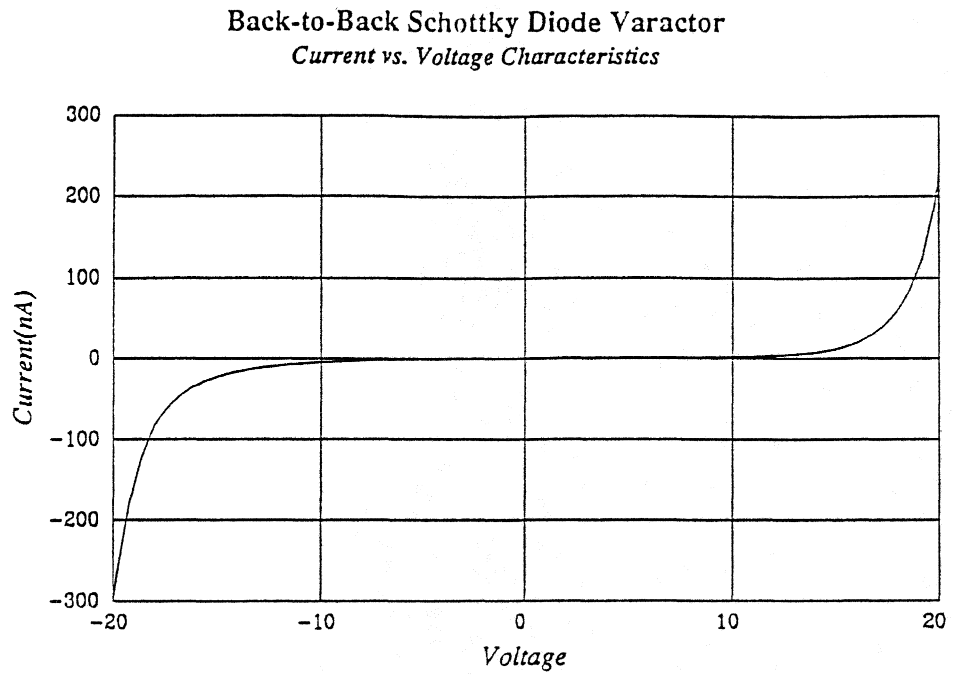


Figure 8


Back-to-Back Schottky Diode Varactor
Current vs. Voltage Characteristics
300
200
100
0
-100
-200
-300
Current(nA)
-20
-10
0
10
20
Voltage

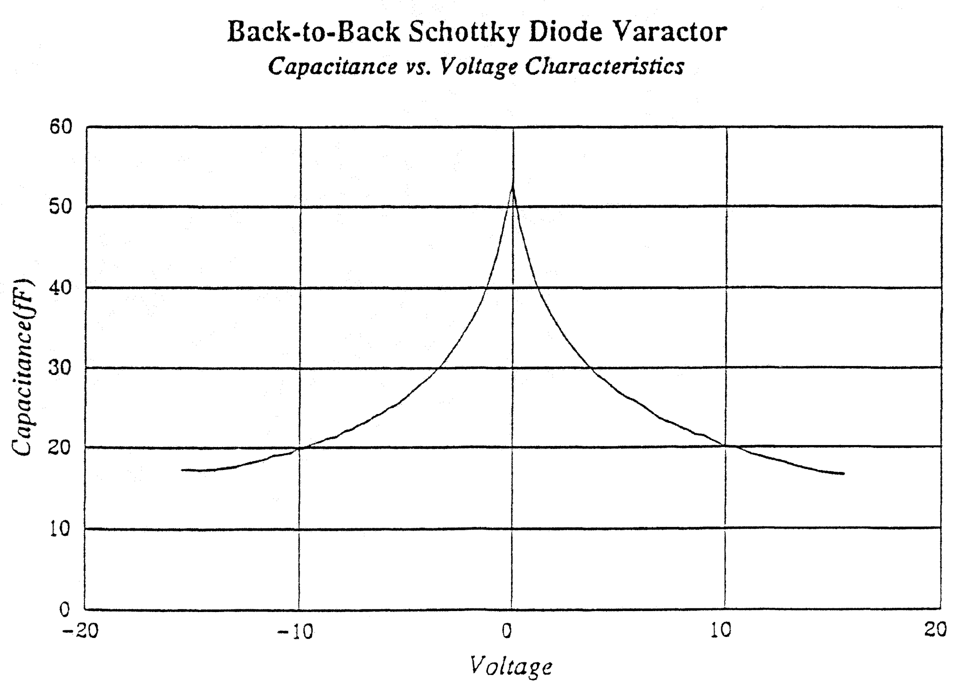

Back-to-Back Schottky Diode Varactor
Capacitance vs. Voltage Characteristics
60
50
40
30
20
10
0
Capacitance(fF)
-20
-10
0
10
20
Voltage

Figure 9

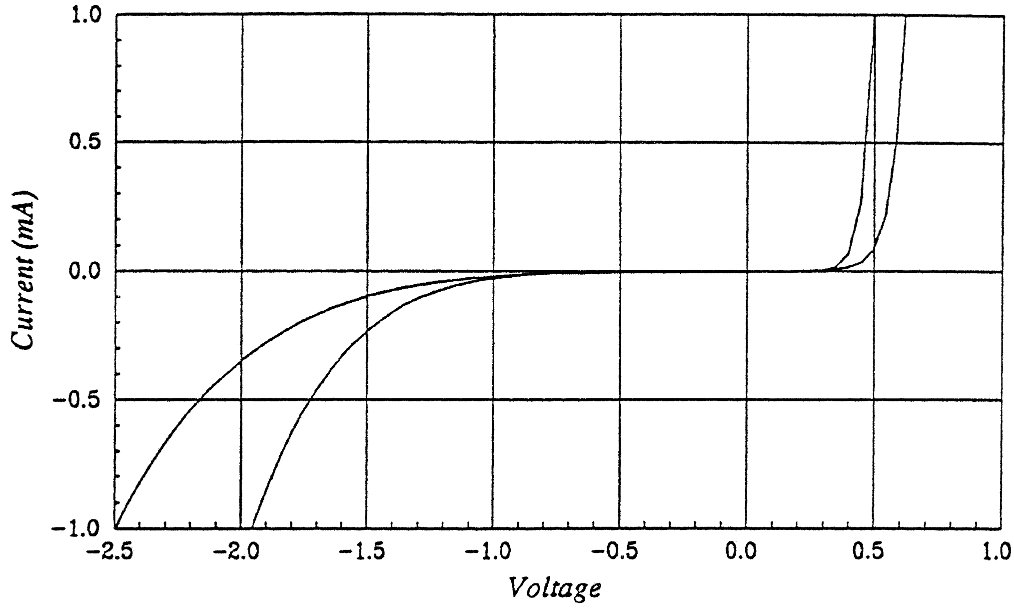


Figure 10