C-1

THE GAP DIODE*: A NEW HIGH FREQUENCY MIXER AND DETECTOR

S. J. J. Teng, P. Chen, F. J. Rosenbaum
Department of Electrical Engineering
Washington University
St. Louis, Missouri 63130
and R. E. Goldwasser
Central Microwave Company
St. Charles, Missouri 63301

Abstract

A new metal-semiconductor device is reported whose I-V characteristic is controlled by a geometric gap between adjacent Schottky barrier regions. An improved performance low turn-on votlage GaAs diode is demonstrated at 10 through 70 GHz.

Introduction

Conventional Schottky barrier junction diodes are widely used in mixer and detector applications at microwave and mm-wave frequencies. Their properties are well known. The forward voltage required to turn on a Schottky diode depends on the difference in work function between the metal and the semiconductor. For GaAs and conventional metal contacts this barrier height is 0.7 volts or greater. There are some applications in which a lower barrier height (and hence lower turn-on voltage) would be advantageous. For example, at mm-wavelengths available signal power levels may not be adequate to drive the device well into forward conduction. This leads to lowered detector sensitivities and reduced mixer performance specifications. Several techniques have been used to lower the effective barrier heights of GaAs Schottky diodes such as high temperature process control[1], and the planar doped barrier[2].

In this work we report a simple and effective means for lowering the turn-on voltage of a high frequency diode to a specified value. This new design permits the use of conventional Schottky metals and is particularly useful with GaAs. Furthermore, it lends itself to a class of devices which may have improved temperature behavior, intermodulation distortion properties and enhanced burn-out capabilities.

Principle of Operation

A cross-sectional view of one implementation of the device is shown in Fig. 1. It consists of an n-type epitaxial layer of GaAs on an n^+ conducting substrate. Stripes of a Schottky metal are deposited either on the surface or in notches in the epi-layer. Thus, a gap exists between adjacent Schottky barrier regions exposing the n-layer. Finally, an ohmic contact is established over the entire surface, connecting the Schottky barrier regions and the n-layer filled gap in parallel. Note that this cell can be repeated across the surface of a wafer.

The principle of operation is as follows. At zero bias the Schottky metals deplete the semiconductor both below the contacts themselves and in the gap between them. By adjusting the width of the gap and the depth of the notch the turn-on voltage for a given doping and choice of metal can be set. Fig. 2b shows contours of equal free charge density, n, normalized to the doping density, N_D, with no bias applied. The cathode contact is at the bottom of the n layer. These results were obtained from numerical simulations[3]. Note the heavily depleted regions under the Schottky contacts and up into the gap as well. These are bounded by the contours $n/N_D = 0.001$. In reverse bias, Fig. 2c, the depletion regions punch through to the cathode contact and the neck between the depletion regions moves down from the gap. Reverse leakage current is supported by free carriers in the gap and in the neck between the depleted regions. In forward bias, Fig. 2a, the depletion regions are retracted toward the metal contacts, thus exposing a conducting channel. Notice that this occurs for forward bias well below that needed to supply charge through the Schottky contacts.

*Patent Applied For

These iso-density plots can be used to predict a number of important features of the device performance: The gap geometry can be used to control the turn-on voltage of the device. The reverse current results from incomplete depletion in the gap which does not completely pinch off because the potential is the same on each of the Schottky contacts. In forward bias charge flows primarily through the gap rather than through the Schottky metals. This means that:

a.) The temperature characteristics of the diode will depend primarily on temperature variation of the mobility of the semiconductor material rather than on that of the Schottky barrier.

b.) The capacitance variation of the device between reverse and forward bias should be less than that of a conventional Schottky diode. Thus the RF impedance of this device should be less sensitive to drive than a conventional Schottky diode.

c.) Since conduction occurs through an ohmic channel, the noise properties of the Gap diode may be significantly different from those of the conventional Schottky.

d.) Likewise, the I-V characteristic will not be exponential but rather more square-law in nature. Thus, nonlinear behavior such as intermodulation distortion and harmonic generation should differ from that of the conventional Schottky diode.

e.) Finally, we expect the burn-out characteristics to be superior to those of the pure Schottky device, because the reverse leakage is not caused by avalanche breakdown and so the associated filament formation and other high field phenomena should not be present.

Figure 3 shows I-V curves for the Gap diode predicted by analysis[3]. The parameter is the width of the gap normalized to the depletion depth (L_D) for the material. Note that a large range of turn-on voltages, from that of the pure Schottky to near zero bias, can be obtained. Control disappears when the gap is widened beyond $2L_D$.

Device Design

Design rules for the Gap diode link the gap width to the active layer doping. As N_D is increased, the gap width must be decreased. For a 2μm gap the appropriate carrier concentration is $\sim 2\times 10^{15}/cm^3$. This value is quite low for mixer applications. A design utilizing $N_D \sim 10^{17}/cm^3$ would require ~0.2μm stripes. Note, however, that the stripe implementation of the gap diode does not require fine mask alignment and hence it can be fabricated without resort to heroic means.

0149-645X/82/0000-0024 $00.75 © 1982 IEEE

Experimental Results

Numerous dc and microwave evaluations of device behavior were carried out on GaAs diodes with $N_D=2\times10^{15}/cm^3$ fabricated with ~2μm stripes. The total device area was maintained large (~$2\times10^{-5}cm^2$) so that conventional wire bond-mesa construction could be used rather than honeycomb or beam lead processing.

Figure 4 shows the experimental I-V characteristics for six Gap diodes fabricated from the same epilayer but with varying gap widths. The right most curve is for a pure Schottky barrier diode. The gap opens toward the left. The mesa diameter for all these devices is 30 μm. Note the similarity to the predicted I-V curves of Fig. 3.

For microwave characterization diodes were wire bonded in 0.030" diameter ceramic packages. Figure 5 compares the detection sensitivities of the gap diode to that of a 1N23C Si point-contact diode and a pure Schottky barrier diode at 10.565 GHz, in the same mount. The Gap diode exhibits about 3/4 the sensitivity of the 1N23C but saturates at higher power levels. When compared to a conventional Schottky diode the advantage of low turn on voltage is readily apparent. The characteristics of this device makes it a good candidate for control applications where good sensitivity and wide dynamic range are desirable.

Zero-bias detection sensitivity measurements were carried out at several frequencies ranging from 10 to 70 Ghz using the same diode in a coaxial mount, iris coupled to an input waveguide. Although these large diameter, low doped devices are far from optimum for operation at such high frequencies, surprisingly good results were obtained as seen in Fig. 6.

Conversion loss of devices with different gap widths has been measured at 10.565 GHz. Lowest conversion loss is obtained with small gap width, low leakage devices. However, for low local oscillator power applications, devices with wider gaps and, hence, lower turn-on voltages give somewhat better performance. The best conversion loss yet seen was 6.1 dB including 1 dB of IF network loss.

The temperature behavior of the Gap diode has been measured and compared to the 1N23C. Preliminary results show much better temperature stability than the point contact device and an improvement over the conventional Schottky diode.

Conclusion

To obtain improved mm-wave performance the active carrier concentration should be increased to the $10^{17}/cm^3$ region. This will require gap widths of 0.2-0.3 μm and active areas of $2\text{-}5\times10^{-6}cm^2$.

We have demonstrated a new device principle. It is possible to produce depletion of carriers under ohmic contact regions. This observation can be applied to other two and three terminal structures which may yield microwave and mm-wave devices with new and desirable properties.

Acknowledgement

This work was supported by the Office of Naval Research under contract SRO-N00014-79-C-0840. We wish to thank Max Yoder for his interest in this work.

References

1. G. Y. Robinson, "Metalurgical and Electrical Properties of Alloyed Ni/Au-Ge Films on n-Type GaAs," Solid-State Electronics, Vol. 18, pp. 331-342, 1975.

2. R. J. Malik, K. Board, L. F. Eastman, C. E. C. Wood, T. R. AuCoin, R. L. Ross, and R. O. Savage, "GaAs Planar Doped Barriers by Molecular Beam Epitaxy," 1980 IEDM Technical Digest, pp. 456-459, IEEE Cat. No. 80CH1616-2.

3. P. Chen and F. J. Rosenbaum, R. E. Goldwasser, "Two-Dimensional Semiconductor Device Simulations Using Small Computer," in preparation.

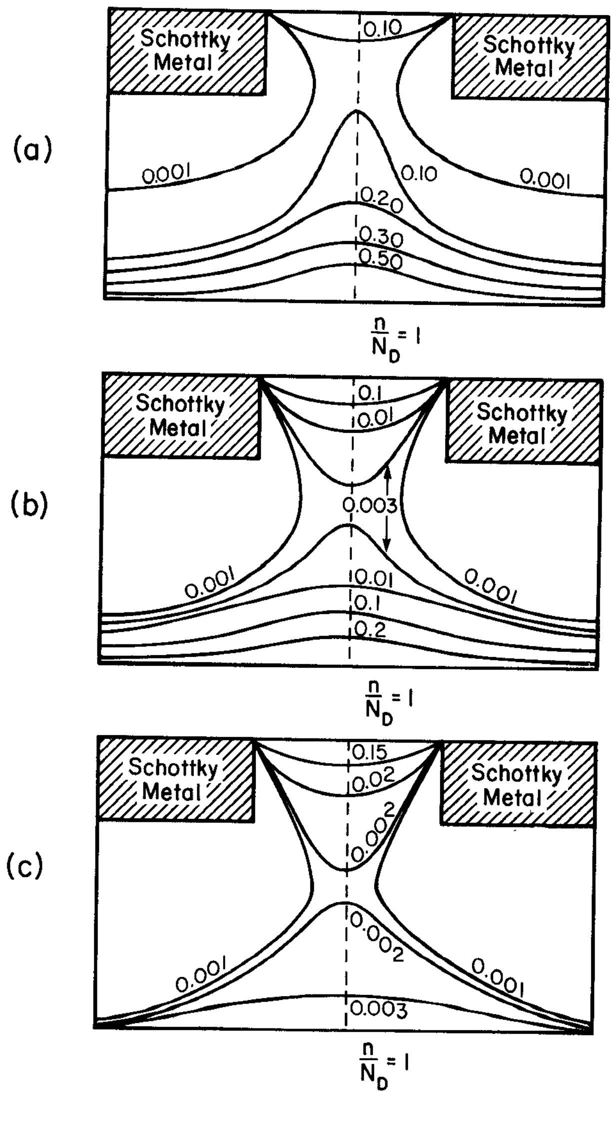

Figure 2. Iso-density lines (n/N_D) for unity normalized gap width ($W/L_D=1$)
a.) Forward bias: 0.3V
b.) Zero bias
c.) Reverse bias: 0.3V

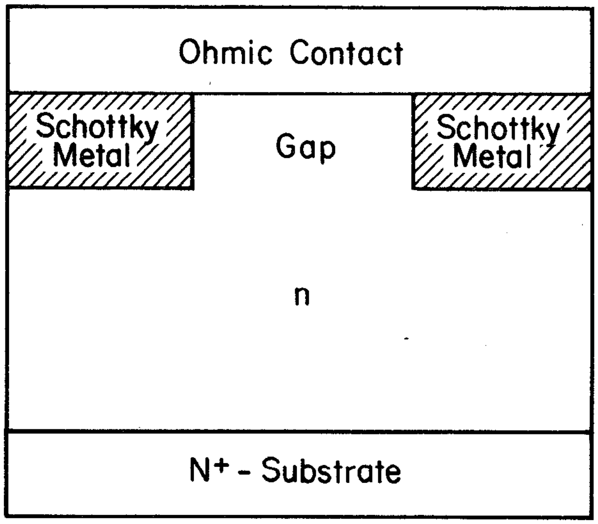

Figure 1. Cross-section of Gap Diode.

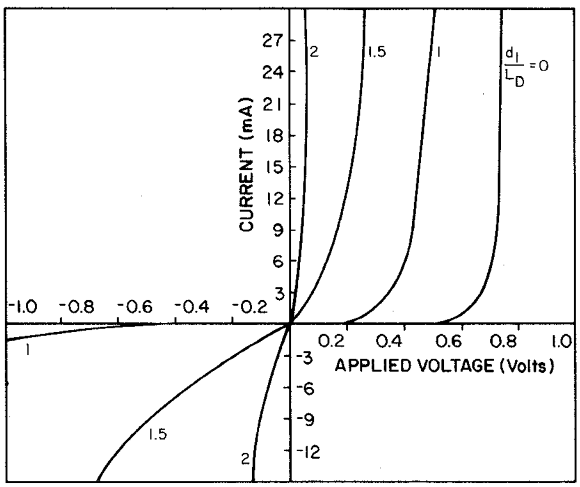

Figure 3. Predicted I-V characteristics with normalized gap width as parameter for a given area.

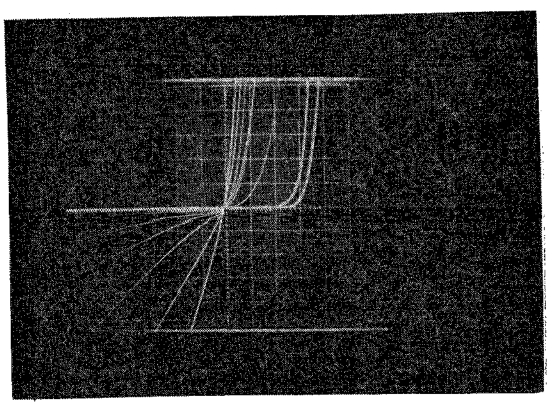

Figure 4. Experimental I-V characteristics for diodes seven different gap widths. Right hand I-V is for pure Schottky barrier diode (zero gap).
Vertical Scale: 50 μA/div
Horizontal Scale: 200 mV/div

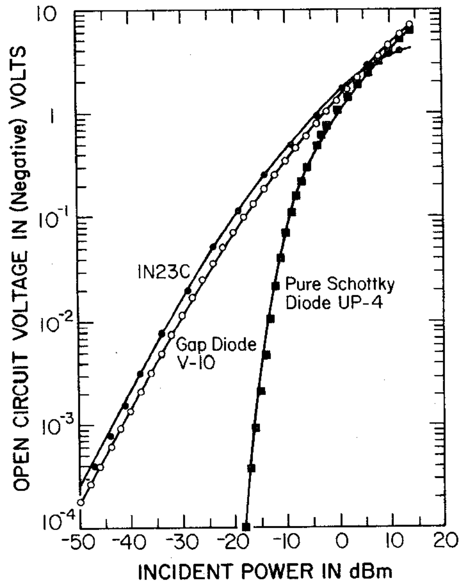

Figure 5. Comparison of detected voltage of Gap diode, 1N23C point contact diode, and a conventional Schottky diode at 10.565 GHz.

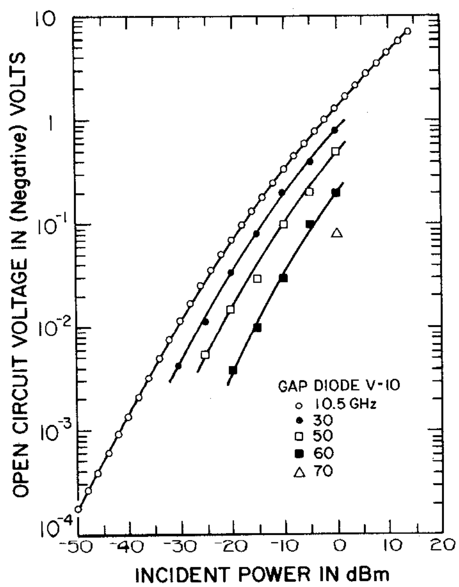

Figure 6. Comparison of detected voltage of Gap diode at 10 to 70 GHz.