GALLIUM ARSENIDE HYPERABRUPT TUNING VARACTORS

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ABSTRACT

Hyperabrupt gallium arsenide tuning varactors have been constructed using vapor phase grown epitaxial gallium arsenide of low-high-low doping profile. Both platinum Schottky and p-n junction devices have been studied. The varactors have exhibited 50 MHz Q at 4 volts reverse bias in excess of 5000, tuning ratios from zero bias to breakdown in excess of 13 to 1, and have been useful in providing linear tuning of an X-band Gunn diode voltage controlled oscillator (VCO). Fine grain tuning linearity and harmonic generation have been studied.

INTRODUCTION

Hyperabrupt varactors have the desirable properties of large capacitance change ratio (in excess of 10 to 1) and the ability to provide a linear frequency versus voltage tuning curve when used to tune the frequency of an oscillator. Silicon hyperabrupt varactors are limited to use at frequencies below 5 GHz because of their low Q (typically 500 at -4 volts and 50 MHz). It was the purpose of this work to develop a GaAs hyperabrupt varactor with a high Q, to allow operation above 5 GHz and to retain desirable hyperabrupt properties.

Gallium arsenide hyperabrupt varactors with the potential of much higher Q are under development at several laboratories. Immorlica, et.al. [1], of Rockwell International Science Center have reported using ion-implantation to produce planar, passivated hyperabrupt gallium arsenide varactors, but have achieved a Q of only 525 for 2.9 pF at 4 volts reverse bias. A maximum capacitance change ratio of 7.5 to 1 was reported for 0 to 17 volts reverse bias.

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Hara, et.al., of Mutsushita Research Institute, Tokyo, Japan, have developed a gallium arsenide hyperabrupt varactor intended for use in UHF TV tuners [2,3]. These diodes employed high-low (H-L) style doping profile and exhibited 10 to 1 capacitance change from 1 to 30 volts and a typical series resistance of 0.18 ohm for a 20 pF (at 1 volt reverse bias) device.

In the present work, hyperabrupt varactors have been fabricated using low-high-low profile epitaxial gallium arsenide. These varactors have exhibited high Q (greater than 4000 for a 1.0 pF junction at 4 volts reverse bias), and the desirable hyperabrupt varactor properties of large capacitance change and ability to linearize VCO tuning.

THEORETICAL CONSIDERATIONS

In a p+/n or Schottky/n-junction diode, if the doping density versus position on the n-side is given by

$$N(x) = B x^{m} \tag{1}$$

the device is said to be hyperabrupt if $m < 0$. It can be shown that for a single L-C resonant circuit, linear tuning may be obtained when $m = -3/2$. However, in practice we have found that for voltage controlled Gunn oscillators in X-band, the frequency variation with bias voltage may be described by

$$f = K \log (1 + V/\varphi) \tag{2}$$

when tuned with a flat profile varactor. Rewriting the equation to describe the frequency variation in terms of the varactor capacitance and imposing the condition that the frequency variation with respect to bias voltage be linear, it can be shown that for linear tuning the varactor capacitance has to vary as

$$C_J = C_{J0} \, e^{-BV} \tag{3}$$

where B is a constant.

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The doping profile contemplated for use in varactor fabrication is shown in Figure 2. It is characterized by a narrow (0.04 to 0.07 micron half width) doping spike located within 0.1 to 0.2 micron of the junction and followed by a 1 to 2 micron region of constant doping. As shown in Figure 2, a Gaussian function followed by a region of constant doping is a good approximation to profiles of this type and can be used in analysis. In Figure 3, a computer generated capacitance voltage (C-V) curve based on the Gaussian approximation is compared to the measured C-V curve of a representative device. Again, agreement is good when replotted semi-logarithmically. The resulting curve (see Figure 4) exhibits a range of exponential behavior, leading to an experimentally verified region of linear tuning as indicated in Figure 3.

Device Fabrication

Hyperabrupt varactors have been constructed from low-high-low (L-H-L) profile epitaxial gallium arsenide, using platinum Schottky and epitaxially grown p-n junctions. The L-H-L profiles used are characterized by a heavily doped peak region (1 to 5 x 10^{17} donors /cc) of width at half height of 0.04 to 0.07 micron and located 0.1 to 0.2 micron from the junction. The peak is followed by a flat profile region of constant doping (from 5 to 10 x 10^{15} donors/cc). The base half width or skirt width (distance from the peak to the beginning of the flat region) is in the range 0.4 to 1.2 microns. In some cases, it was necessary to alter the as-grown doping spike location in order to achieve the required capacitance versus voltage characteristic. Both anodic oxidation and sputter etching were used successfully for this purpose.

Schottky varactors were fabricated in mesa chip form by sputtering 2000 Å of platinum through a photoresist mask on the sputter etch cleaned epitaxial surface. After lifting the resist, mesas were formed and the chips separated by conventional techniques of etching, scribing and cleaving.

The p-n junction devices utilized a 1 to 2 micron epitaxially grown (1 to 3 x 10^{18} acceptors/cc) p+ layer, deposited in a separate reactor. This procedure allowed spike position tailoring, if required. Ohmic contact was made to the p+ region using a sintered gold - zinc metallization.

In the case of Schottky or p+ junctions, three mil diameter mesas were used on 10 mil square chips of 3 mil total thickness. Chips were mounted for evaluation in 80 mil diameter ceramic, double prong diode packages having a case capacitance of 0.17 pF. Gold tin eutectic solder was used for chip mounting, and connection to the mesa was made using a 0.6 nH, 1/4 x 5 mil gold ribbon.

Device Characterization

The diodes were tested for breakdown voltage at 10 nA; capacitance versus reverse bias (C-V curve) at 1 MHz; Q, scaled to 50 MHz (DeLoach method); and tuning linearity when used to tune an X-band Gunn diode VCO. Typical C-V curves for two lots of hyperabrupt varactors from the same wafer are compared with that of a flat profile GaAs varactor in Figure 5. The two hyperabrupt lots differ in that the doping profile peak was placed at 0.1 micron from the junction in one case, 0.18 micron in the second. Figure 6 compares the tuning characteristics obtained for the two sets of varactors in the Gunn VCO. Ranges of linear tuning occurred for both hyperabrupt devices. However, the 0.1 micron peak position device provided 150 MHz of linear tuning over 1 to 17 volts, while the 0.18 micron peak position device provided only 60 MHz over 5 to 10 volts. For comparison, the tuning curve for the flat profile device is shown.

A data summary for four types of profiles appears in Table I. The performance trade-offs are shown in that devices with the largest ranges of linear tuning have the lowest Q values. No difference between Schottky and p+ devices was seen with respect to Q or linear tuning behavior. Q's as high as 2500 referred to 50 MHz were measured for 4.5 pF, p+ junction devices at 4 volts reverse bias. The p+ devices, however, exhibited sharper breakdowns and lower reverse leakage currents at elevated temperatures (typically 2 nA at 150°C and 80% of breakdown).

Fine grain or differential linearity properties of the hyperabrupt varactors were compared to those of a flat profile gallium arsenide device using a microwave link analyser and Gunn diode VCO operating at 12 GHz. As shown in Figure 7, by careful selection of the bias point, very good differential linearity can be achieved. Best differential linearity, less than 1/2%, was obtained for the hyperabrupt varactor at -6 volts bias. The standard varactor exhibited 14% differential linearity.

A study of harmonic generation due to tuning varactor multiplication effects has been carried out using both hyperabrupt and conventional flat profile units. Second harmonic power radiated from an antenna attached to an X-band Gunn diode oscillator was monitored versus varactor bias for both conventional and hyperabrupt varactors. The results are shown in Figure 8. At -6 volts bias, the second harmonic was 3.4 dB down using the hyperabrupt diode and 14 dB down with the conventional unit.

Although the hyperabrupt varactor exhibits large harmonic generation in comparison to a flat profile varactor, its usefulness is not necessarily limited.

Circuit designs involving hyperabrupt diodes can avoid harmonic problems by using larger capacitance varactors in a decoupled condition to achieve large tuning bandwidth and at the same time low harmonic generation.

CONCLUSION

Hyperabrupt tuning varactors have been fabricated using vapor-phase grown epitaxial gallium arsenide of low-high-low doping profile. Both Schottky and grown p+ junctions have been investigated. Diodes have exhibited a 50 MHz, Q at 4 volts reverse bias in excess of 5000, tuning ratios from zero bias to breakdown in excess of 13 to 1, and the ability to linearize X-band Gunn diode VCO tuning.

REFERENCES

1. Immorlica, A.A., and Eisen, F.H., "Planar Passivated GaAs Hyperabrupt Varactor Diodes", Proceedings of the Sixth Biennial Cornell Electrical Engineering Conference on Active Microwave Semiconductor Devices and Circuits, p. 151, August (1977).
2. Hara, T., Niikura, I., Hozuki, T., Toyoda, N., and Mihara, M., "GaAs Varactors for UHF TV", IEEE Trans. Consumer Electronics, Vol CE-23, p. 433, November (1977).
3. Hara, T., Niikura, I., Toyoda, N., and Mihara, M., "High Q GaAs Varactor Diodes", IEEE Trans., Vol ED-25, p. 501, May (1978).

SKETCH OF THE GUNN DIODE VCO USED IN HYPERABRUPT VARACTOR EVALUATION

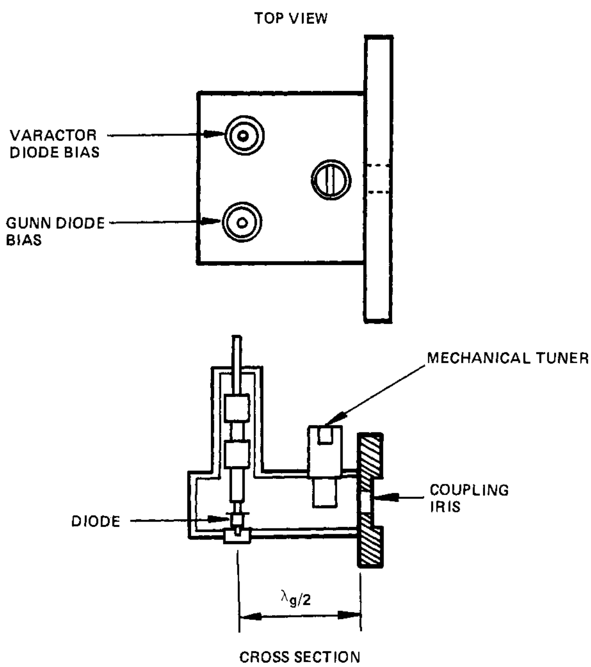

FIGURE 1.

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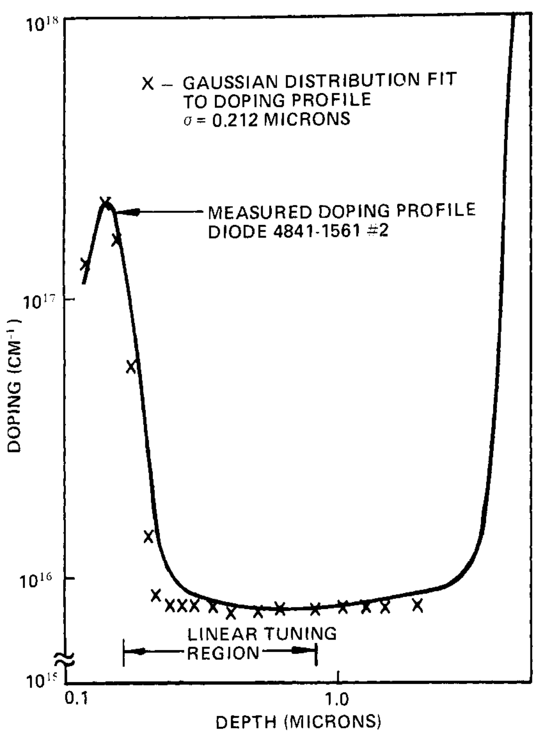

FIGURE 2. MEASURED DOPING PROFILE AND GAUSSIAN DISTRIBUTION USED TO APPROXIMATE THE PROFILE FOR ANALYSIS

D-16380A

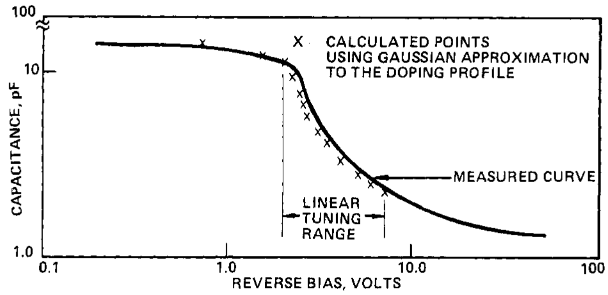

FIGURE 3. MEASURED CAPACITANCE VS VOLTAGE CHARACTERISTIC FOR DIODE 4841-S61 #2 COMPARED WITH THE CAPACITANCE VS VOLTAGE CURVE CALCULATED USING THE GAUSSIAN APPROXIMATION TO THE PROFILE

D-16368

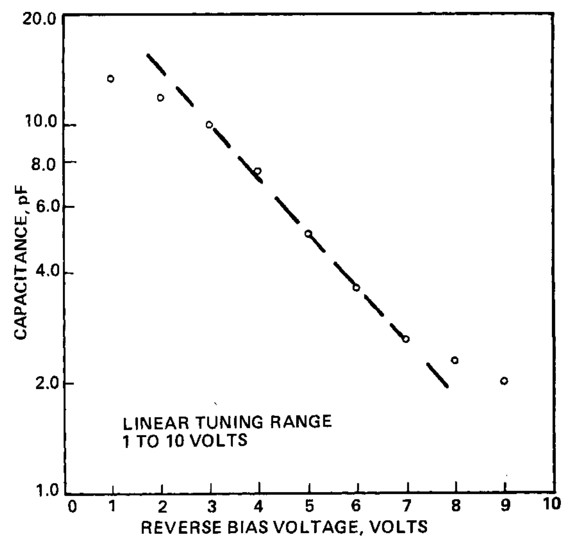

FIGURE 4. CAPACITANCE VS VOLTAGE CHARACTERISTIC FOR THE DEVICE OF FIGURE 3.

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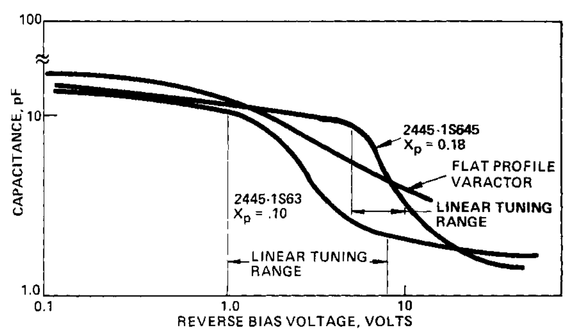

FIGURE 5. EFFECT OF DOPING PROFILE PEAK POSITION ON HYPERABRUPT VARACTOR CAPACITANCE VS. VOLTAGE CURVE

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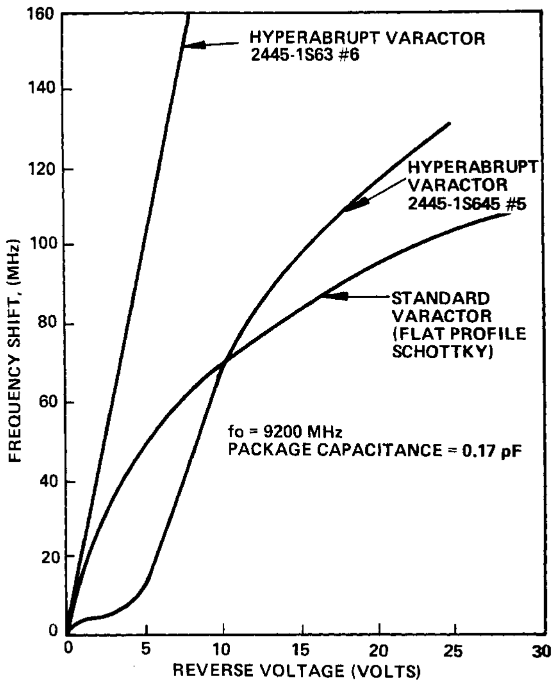

FIGURE 6. COMPARISON OF THE TUNING CURVES OF A GUNN VCO WITH TWO HYPERABRUPT AND ONE FLAT PROFILE VARACTOR

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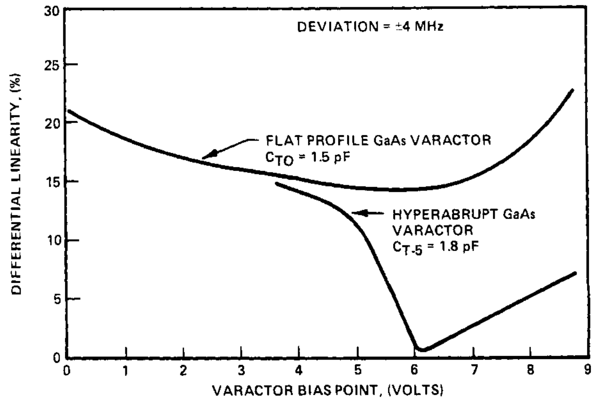

FIGURE 7. DIFFERENTIAL LINEARITY VERSUS BIAS POINT FOR A 12 GHz GUNN DIODE VCO TUNED WITH A CONVENTIONAL OR HYPERABRUPT GaAs TUNING VARACTOR.

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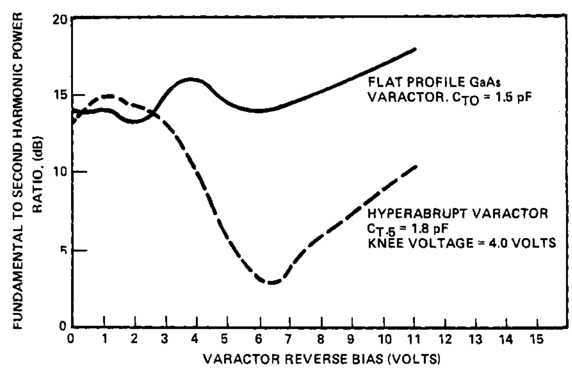

FIGURE 8. RADIATED SECOND HARMONIC TO FUNDAMENTAL POWER RATIO FOR A 12 GHz GUNN DIODE VCO TUNED WITH A CONVENTIONAL OR HYPERABRUPT GaAs TUNING VARACTOR.

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CHARACTERISTICS OF VARIOUS HYPERABRUPT VARACTOR WAFERS

CURVE	X_p MICRONS	N_p $\times 10^{17}$	Δ MICRONS	N_D $\times 10^{15}$	W MICRONS	CHIP C_{TO}/C_{TVB}	LINEAR TUNING MHz	LINEAR TUNING VOLTS	Q −4 VOLTS 50 MHz
1	.13	2.0	.05	7.0	4.1	11.3	65	1 TO 5	4500
2	.14	2.2	.05	8.0	4.2	11.8	100	2 TO 7	5000
3	.11	2.7	.07	2.1	4.7	13.0	140	1 TO 10	1500
4	.10	3.5	.04	5.0	3.8	6.7	155	0 TO 8	2500

0.7 pF DIODE AT −4 VOLTS

X_p – PEAK POSITION FROM SURFACE.
N_p – PEAK CARRIER DENSITY.
N_D – FLAT REGION CARRIER DENSITY.
W – TOTAL EPITAXIAL THICKNESS TO TERMINATION OF FLAT REGION.

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TABLE I.