A 22 PERCENT C.W. EFFICIENCY SOLID STATE MICROWAVE OSCILLATOR *

B. Kramer, A. Farrayre and L. Hollan
Laboratoires d'Electronique et de Physique Appliquée
3, avenue Descartes
94 - Limeil-Brevannes

E. Constant and G. Salmer
Faculté des Sciences de Lille, Bat. P3, B.P. 36
59 - Lille
FRANCE

Abstract

Operation of GaAs Schottky-barrier IMPATT diodes is reported. We describe the technology, the electrical characterization and the microwave coaxial measurements. Efficiencies of 22% at 6.5 GHz and 18.5 % at 12 GHz were obtained. Computer calculations indicate that the efficiency of these devices may be considerably higher.

The promises given by the GaAs IMPATT diodes are fully held because we demonstrate clearly the possibility of obtaining C.W. efficiencies greater than 20% in X band.

These results are better than the preceding best GaAs world-results of Microstate, which were 17 %[1], and quite higher than the best results for Si IMPATT diodes. The reasons which explain the superiority of GaAs in front of Si are, now, well known :

- The ratio between avalanche zone and transit zone is smaller because the ionization rates of electrons and holes are equal and are rapidly increasing functions of the electric field.
- The second derivative of the ionization rate in respect to the electric field is smaller so that the phase between electric field and current in the avalanche zone is around $\pi/2$.

First we describe the technology of fabricating our diodes. They are made from gazeous epitaxial N layers grown on Si-doped, 3.2 10^{-3} Ω.cm, substrates. The junction is a gold Schottky-barrier, the barrier height is 0.8 eV and the quality factor n increases from 1.04 at 380°K to 1.29 at 300°K.

Figure 1 gives the schema of a typical diode. After thinning the wafer to a total thickness of 35 µm and realizing the Schottky-barrier junction, the gold film is thickened up to 3 µm. Then a silver layer, 30 µm thick, is electroplated, for heat-sinking and easy inverted mounting. Finally, 2 µm of gold are put down to facilitate the mount of the diode on the pillar. On the other side of the wafer, gold electroplated contact is realized on the n^{++} substrate. This is also a Schottky-barrier, but forward biased. The thickness of the gold layer is 2 µm, to protect the diode during the operation of thermal compression wire bonding. Circular mesas, defined by SiO_2 masking dots, are then realized by etching from the n^{++} side. Photo 1 of the figure 2, taken with a S.E.M., shows the shape of a mesa of 80 µm diameter. On the photo 2, we can see that there is no under-etching, and a good definition of the working junction area. We have tried to respect the theoretical angle of 70°, decreasing the electric field on the edges near the junction. The individual diodes are separated by cutting the silver pedestral with a razor blade and mounted with soft solder in standard varactor packages S_4.

We describe now in detail the characterization results for two representative series of diodes on which the best efficiency results were obtained, i.e. 36 A and 8 A.

The doping concentration profile for the 36 A was of the Read type[2], while, for the 8 A, it was uniformly decreasing towards the substrate. The growth-process of the 36 A epitaxial layer has been especially programmed in accordance with the results of computer calculations of the theoretical efficiencies corresponding to various doping concentration profiles. With our computer model, a flat profile gives a maximum theoretical efficiency of 17 % with the 8 A profile this increases to about 19 %, while it can reach 28 % with the 36 A profile. The epitaxial n layers have about the same thickness, but for the 36 A, the layer is fully depleted at breakdown and the optimum frequency of operation corresponds to a transit-time length at breakdown of about 6 µm. For the 8 A, the depleted length at breakdown is only 3 µm and consequently the optimum frequency is higher.

The breakdown voltages (extrapolated to 0 mA) are 60 ± 10 volts for the 36 A and 45 ± 1 volt for the 8 A.

Figure 3 shows the series resistances viewed at the package terminals. They have a very different behaviour. Indeed, the value for the 36 A is very high at small bias and then goes down to a quite small value, about 0.1 ohm, at breakdown. For the 8 A, the law of variation with bias and the value at breakdown, around 0.4 ohms, are more usual. The H.F. small signal impedances, shown on figure 4, corroborate the preceding remarks. The encapsulated negative resistance is rather small, about 10 ohms, but when referred to the inner device terminals, this becomes about 200 ohms for the 36 A and 40 ohms for the 8 A.

Finally we make the output power measurements in a carefully calibrated set-up, including filtering of the second and third harmonics as well as of the subharmonic 1/2.

The device was mounted in a two-slug 50 ohms coaxial cavity. To lower the contact losses, particularly important at 12 GHz, and improve the measurements reliability, we realized special cavities where the first slug is cut in the metal bulk and surrounds the device.

With these cavities we obtained 18.5 percent efficiency with 500 mW output power at 12 GHz on the 8 A series. One can see, on figure 5, that half of the diodes measured gave more than 16 % efficiency.

The comparison in efficiency and output power between the two series is shown on figure 6. One may point out that the 36 A have a better efficiency, 21.8 %, than the 8 A, but there are some restrictions for the advantages to the 36 A :

- The optimum frequency of oscillation is about half that of the 8 A ;
- The homogeneity of the results is less good because only 40 % of the diodes have an efficiency greater than 16 % ;
- The optimum temperature of the heat sink is lower, 0°C, than for the 8 A, about 20°C ;
- The output power and bandwidth are smaller than for the 8 A.

We attribute the two last points to the lack of avalanche uniformity in the diode. According to measurements, not described here, only about 30 % of the total device area actually works. The rather high thermal resistance measured on these diodes, 30 to 45°C/W is also attributable to this phenomenon.

In conclusion, our basic objective of 20 % output efficiency has been experimentally demonstrated. According to computer calculations, up to 30 % would be possible.

We are currently working towards improving the reproducibility of the best results, increasing the output power at high efficiency and evaluating the reliability of these devices.

References

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1 C. Kim
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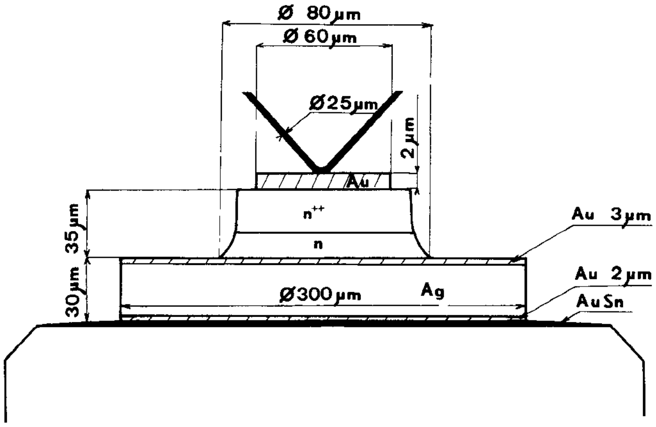

FIG. 1 - Schema of a Schottky-barrier avalanche diode

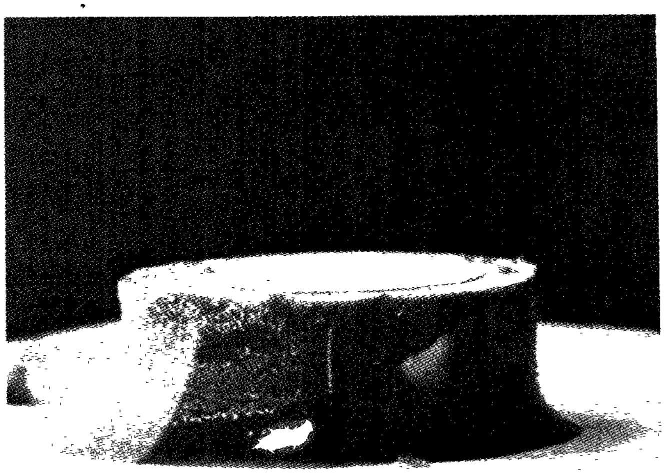

Photo 1 : Photo of a 80 microns diameter mesa

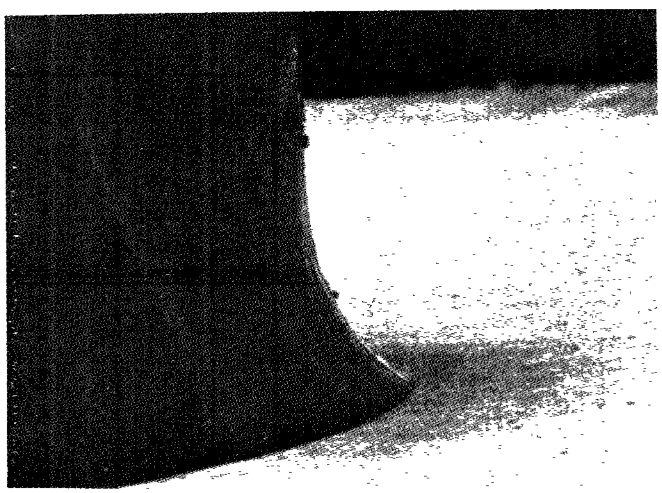

Photo 2 : Photo of the working area and of the side of the mesa

FIG. 2

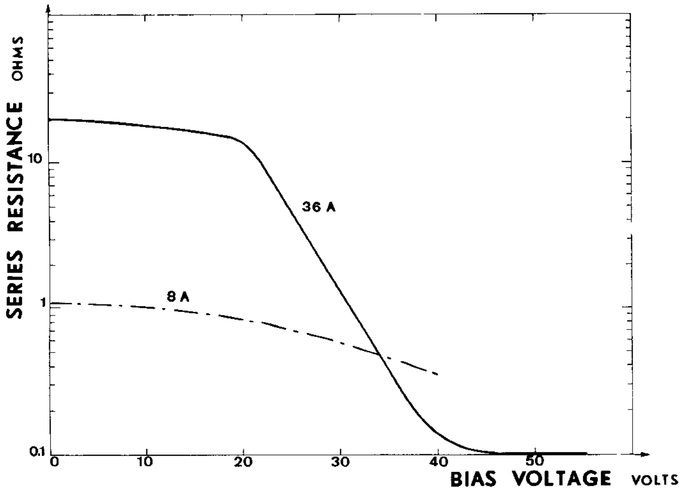

FIG. 3 - Series resistances for 36 A and 8 A series

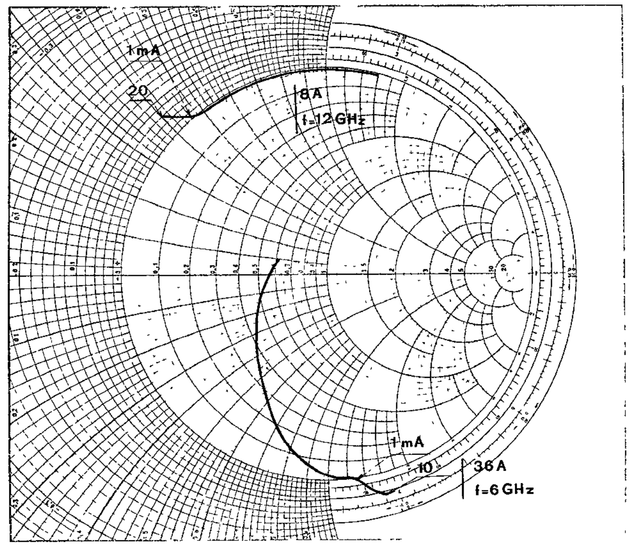

FIG. 4 - Microwave impedances for 36 A and 8 A series

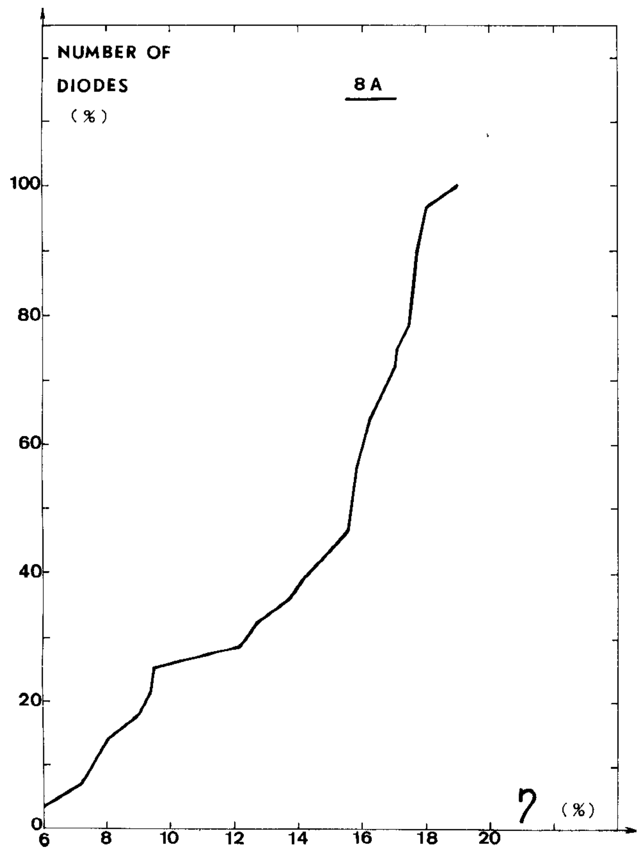

FIG. 5 - Uniformity of the efficiency results on 8 A series

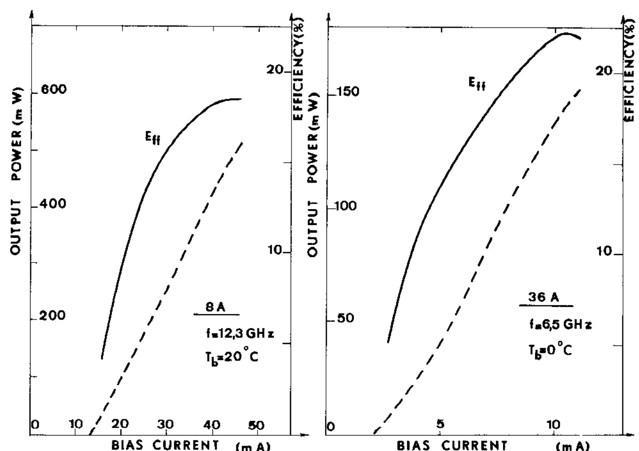

FIG. 6 - Best powers and efficiencies for 36 A and 8 A series

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