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Continuous Microwave Oscillations of Current in GaAs

Previous work[1] has shown that microwave oscillations can be generated by applying a strong electric field to a semiconductor such as *n*-type GaAs or InP. The results obtained by using extremely short pulses with low duty cycle were sufficiently promising to make it worthwhile, by appropriate thermal design of the specimen, to explore the possibility of obtaining greater average power or longer pulse lengths. This work has now progressed to the point where continuous operation has been obtained at room temperature.[2]

In the previous work, no attempt was made to remove heat from the GaAs other than by conduction through the plastic in which the structure was encapsulated. This fact imposed a stringent limitation on the power that could be dissipated without damage to the specimen. When attempts were made to exceed this limitation, the specimen invariably developed a short circuit, which could be shown by microsectioning to be due to the appearance of a conducting channel between the alloyed Sn electrodes. This difficulty could be overcome to some extent by bonding the body of Sn forming one of the electrodes to a copper heat sink, but the results obtained by this method were not really satisfactory, possibly because of the ease with which Sn appears to be able to penetrate the GaAs under operating conditions to form a channel. As an alternative approach to the technique of alloying individual Sn contacts to small discs of GaAs, a batch fabrication process was used in which ohmic contacts were evaporated onto both sides of a wafer of GaAs of the appropriate thickness. This wafer was then cut up with a wire saw into many small dice 175-250 microns square, each of which could be used as the active component of a microwave oscillator device. Individual dice were put into intimate thermal contact with either one or two heat sinks of copper. These heat sinks were in the form of rods, 3/8 in. long and 3/16 in. in diameter, fitted into a corresponding hole in a copper or brass block. In the case where only one heat sink was used, one face of the active die was soldered to the end of the copper rod, and a very thin copper ribbon was soldered to the opposite face. The die was partially enclosed by a metalized alumina ring which was soldered to the heat sink and to the copper ribbon, so giving mechanical rigidity to the structure. When two heat sinks were used, one in contact with each face of the die, efficient heat transfer was obtained by using films of In compressed between the die and the heat sinks, as suggested by Marinace.[3] An improvement in breakdown behaviour under the high electric fields employed was obtained by surrounding the die with a drop of silicone oil.

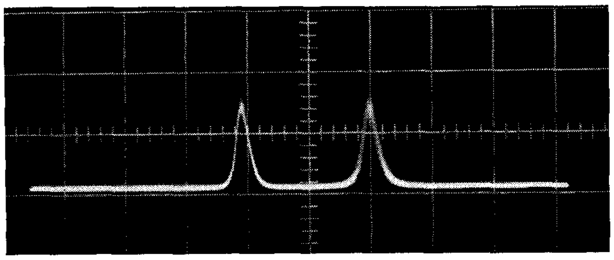
In order to extract useful energy from the oscillations of current produced under the influence of an applied electric field, one terminal of the device was connected to the live side of the source of dc or pulsed power, and in addition was bypassed to ground for radio frequencies. The other terminal was connected to the inner conductor of a coaxial cavity, being thus grounded from the point of view of the power source through a short circuit at one end of the cavity. The length of the inner conductor could be varied, and the points at which the device and an external load (50 Ω) were tapped on the inner conductor could be separately adjusted along the length of the cavity. In this way the impedance presented to the device could be varied over a wide range. For pulsed operation, power was derived from a conventional pulse generator capable of delivering 1A into a 50Ω load. Direct current for continuous operation was supplied by a regulated power supply.

It was found that devices with a single heat sink in which the thickness of the *n*-type GaAs was approximately 100 microns and the resistivity was approximately 0.5 Ω cm were capable only of pulsed operation. Typical operating conditions were: pulse length, 1 μsec; pulse period, 20 μsec (5% duty cycle); pulse voltage, 30 V; pulse current, 0.4 A. Under these conditions, the cavity could be adjusted, for nearly every sample, so that an average power in excess of 50 mW was delivered to an external load, corresponding to 1W peak power. The frequency was normally about 800 Mc/sec, as expected from the electrical length of the GaAs. By adjustment of the cavity it was possible to vary the frequency over a range of at least 100 Mc/sec, and in a few cases between 0.8 and 2 Gc/sec at reduced power. Selected devices were found to be capable of satisfactory operation at duty cycles as high as 25%, indicating that continuous operation should be possible in principle, although these particular devices failed when this was attempted.

Elementary considerations of heat flow show that, if there is good thermal contact between the GaAs and the heat sink, the maximum temperature varies as $(L/n)^2$, where L is the thickness (electrical length) of the GaAs die, and n is the number of heat sinks. Devices were therefore prepared, from the same crystal of GaAs as had provided the previous devices, in which L was reduced to 30 microns, and the double heat sink construction described above was adopted. It appears that during the preparation of this particular batch of devices some contamination occurred, as the apparent resistivity (estimated from device resistance and geometry) increased from 0.5Ω cm to about 3Ω cm and was accompanied by a corresponding decrease in threshold current. Either as a result of this, or of the improved thermal properties, continuous operation above the threshold for oscillation was found to be possible for a number of devices.

Tests of these devices in the same rf cavity described above showed that continuous rf power could be generated at frequencies in the range 4 to 7 Gc/sec. Figure 1 shows the response of a spectrum analyzer to the signal from a GaAs oscillator (the right-hand peak) compared with that from a signal generator operating at 6.30 Gc/sec (the left-hand peak). The dispersion is 15 Mc/sec per major division. In both cases the apparent line width is limited by the resolution of the spectrum analyzer. It is found that the line width of the oscillations in the GaAs is often very dependent on the applied voltage and on the adjustment of the cavity, and that signals may be present at several different frequencies simultaneously. In particular, very strong signals may be present in the range 500 to 1500 Mc/sec; their existence is usually, but not always, accompanied by the appearance of several rather broad signals in the 4 to 7 Gc/sec range.[4] In some cases, however, a single high frequency signal is accompanied by the appearance of a large amount of power in the lower frequency range. This fact makes it necessary to exercise great care in measuring the power delivered to a broadband load such as a bolometer power meter. If a high pass filter is not used, the meter will measure the sum of the low- and high-frequency powers, and adjustment of the circuit to optimize the meter reading will ensure that the spurious low frequency signal is maximized. In this way it is possible to overestimate the level of the high-frequency power by several orders of magnitude. In the case illustrated, a 4 Gc/sec high pass filter was inserted between the bolometer and the cavity output. The power measured in this way was 17 μW with an input power of 8.4 V at 175 mA (1.5 W). Operation under these conditions was sustained over a period of 100 hours. With different adjustments, a signal could be obtained at 7.0 Gc/sec but with reduced power.

Figure 1 **Spectrum analyzer display of the output signal from a continuously operating GaAs device compared with a 6.30 Gc/sec marker signal on the left. The dispersion is 15 Mc/sec per cm; frequency increases to the right.** *In both cases the apparent line width is limited by the resolution of the spectrum analyzer. The output power under these conditions was 17 μW.*



The reason why the efficiency was much lower than would have been expected from previous work[1] is not fully understood. It may be partly due to the fact that the cavity, being designed for lower frequencies, has rather large losses at high frequencies, but it is believed also to be associated with the fact that the resistivity of the GaAs had undergone a change during device manufacture. The impurities responsible for this change probably did not diffuse uniformly into the crystal, and so the current density and electric field may have been very nonuniformly distributed. This might reduce the active volume of the die to a very small fraction of the total, without reducing the dc power in proportion. Some confirmation of this idea may be obtained from the fact that the threshold voltage is sometimes less and the frequency of oscillation higher than would be expected from the thickness of the die, suggesting the electric field has been redistributed in such a way as to reduce the effective electrical length.

References

1. J. B. Gunn, *IBM Journal* 8, 141 (1964).
2. It is understood that continuous operation has also been observed by B. W. Hakki and J. C. Irvin at Bell Telephone Laboratories but details are not available.
3. J. C. Marinace, *IBM Journal*, this issue: 8, 543 (1964).
4. These low-frequency oscillations are believed to be ordinary negative resistance oscillations of a low frequency mode of the cavity, excited by the drop in *average* current which occurs when the voltage exceeds the threshold for oscillation at high frequencies. A shunt resistor of 50 Ω connected across the rf bypass capacitor of the cavity was found to be helpful in suppressing these oscillations, and was used in all experiments on continuous operation.

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