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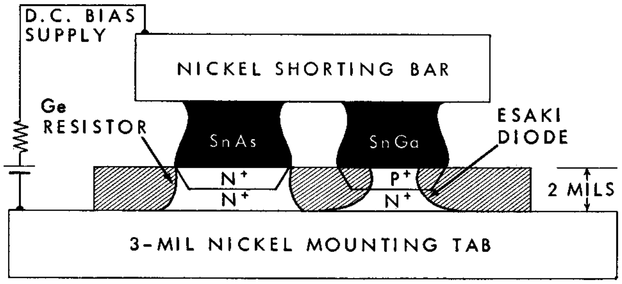
A 3000-Mc Lumped-Parameter Oscillator Using an Esaki Negative-Resistance Diode

The use of the negative-resistance diode discovered by L. Esaki[1] (sometimes referred to as the tunnel diode) in very-high-frequency oscillator circuits employing wave guides and cavities as tuned elements has met with difficulties as a result of so-called parasitic oscillations that arise from the necessity of driving the circuit from a very low-impedance dc source.[2] This communication describes a different design approach, based on lumped-parameter principles, which is free from this type of biasing problem. This approach has produced oscillators which operate well into the microwave region (3000 Mc) where it has not previously been thought profitable to employ only lumped-parameter elements.

The structure employed in these oscillators, shown schematically in Fig. 1, consists of a highly doped n-type germanium wafer, about 2 mils thick, which is soldered to a 3-mil nickel mounting tab which serves as one electrode of the circuit. Two tin impurity dots, one doped with gallium, the other with arsenic, are alloyed to the n-type wafer in close proximity to each other. The SnGa dot forms a recrystallized p region which makes an abrupt junction with the heavily doped n material. This produces a negative resistance of the Esaki type when a forward bias in the region of 50 to 350 mv is applied. The SnAs dot, on the other hand, merely forms an ohmic contact to the n-type wafer. If the resistance between the SnAs dot and the mounting tab is smaller than the absolute value of the negative resistance of the Esaki diode, then the system oscillates at a very high frequency when a shorting bar, which acts as the second electrode of the circuit, is connected as shown. A biasing current then flows through the resistive part of the circuit of sufficient magnitude to produce a dc voltage across the Esaki diode to make it behave as a negative resistance.

Figure 1 **Schematic cross section of the semiconductor microwave oscillator.**
(Shaded area is heavily doped n-type germanium wafer.)



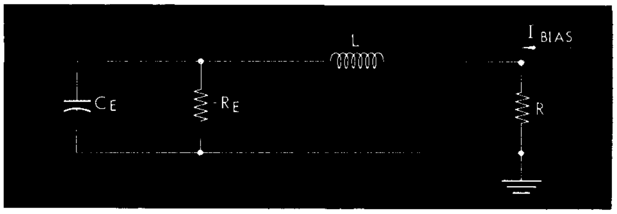


Figure 2 **Simplified equivalent circuit of the microwave Esaki diode oscillator.**

The oscillator frequency is increased as the dimensions of the dots and their spacing decrease. It has been found that the frequency of such an oscillator structure can be increased by etching away the shaded areas of the Ge wafer (Fig. 1). This etching procedure has the effect of reducing the area of the Esaki diode junction, hence also its capacitance. Etching also isolates the bias resistance part of the circuit from the diode part and suggests the simplified equivalent lumped-parameter circuit of Fig. 2. Here, the Esaki diode part of the circuit is represented by a negative resistance $-R_E$ shunted by a capacitance C_E. The bulk resistance of the diode is not explicitly represented in this simplification. The bias resistor, which is concentrated under the SnAs dot, is represented by R and the loop inductance of the circuit is represented by L. A necessary condition for oscillation is that $R<|-R_E|$.

Experimentally, the frequency of a given oscillator has been found to increase as the diameter of the Esaki diode junction area is decreased. Table 1 shows the results of measurements for one oscillator.

Table 1

Frequency in Mc	*Diameter of Esaki diode junction in mils*
1490	3.5
1850	2.9
2240	2.4

The resistor portion of the germanium was covered with stop-off wax, and for each successive measurement shown in Table 1, the Esaki diode portion was electrolytically etched in dilute KOH. This etching action concentrates the removal of germanium in the vicinity of the junction so that the junction capacitance is mainly affected while the loop inductance is essentially unchanged. This condition will not hold if the etching is continued to the point where the germanium becomes a very thin pedestal and contributes to the total loop inductance. Assuming that the junction is uniform over its area, and that area is proportional to the square of the measured diameter, then these results strongly suggest that for this oscillator, in the frequency range indicated, the frequency is very nearly inversely proportional to the square root of the junction capacitance.

It has also been found experimentally that the frequency generally decreases slightly as the forward dc bias is increased. For a typical oscillator operating at 2200 Mc, the frequency decreased approximately 30 Mc as the voltage was increased by 30 mv. This decrease in frequency is consistent with increase in capacitance to be expected with increasing forward bias, but the change in negative resistance with bias, which is not accurately known for these units, can also have an effect. The range of forward bias voltage (normally on the order of 0.1 volt) over which the oscillations are sustained is so small, and the experimental error of measurement so large, that the exact functional relationship between frequency and bias cannot be readily deduced from measurements made thus far.

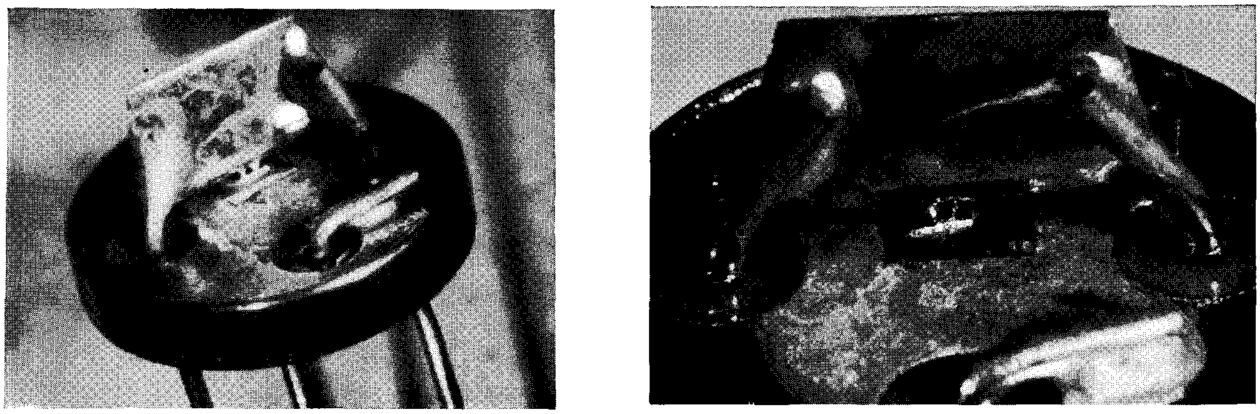
For convenience of making electrical connections to the oscillator structure, the units have been mounted on conventional 3-pin circular transistor headers as shown in Fig. 3. The dc bias is applied between the center pin which is soldered to the base of the header and one of the two outer pins which support the shorting bar. The frequency has been found to be essentially unaffected by the lengths and positions of the leads to the external dc bias supply so long as the resistance in the supply loop is high compared to the resistance of the germanium resistor in the oscillator structure. Since these resistors have typical values of about 50 milliohms, the power supply impedance will be sufficiently high if it is one ohm, a condition which is easily achieved in practice.

The frequency is measured by placing a small length of wire, which serves as a pick-up antenna, near the oscillator and mixing the picked-up signal with that of a known oscillator, then detecting the difference frequency on a General Radio i-f amplifier and detector. It has been found that the use of this type of loose coupling prevents the generation of spurious signals, produced by interactions of the strong local oscillator signal with the nonlinearities of the Esaki diode structure, which otherwise would make the determination of the true fundamental frequency difficult.

Other methods of detecting the oscillations have included strongly coupling the output into a coaxial line which is directly connected to a receiving system. These methods, along with a more detailed analysis of the oscillator, including efficiency and rf power, will be dealt with in a subsequent publication. The lack of influence of the power supply wires on frequency may be attributed to the fact that the header leads are of much greater inductance than the loop inductance of the oscillator structure itself, hence they act as rf chokes. The dimensions of the critical portions of the oscillator are small compared to the wavelength of the oscillations even at *S*-band frequencies.

Fig. 4 is a photomicrograph of an oscillator which oscillated at a fundamental frequency of 3010 Mc. The significant features shown correspond to those in the schematic cross section of Fig. 1, the Esaki diode portion being the right pedestal and the germanium resistor the thicker pedestal on the left. The *p-n* junction is almost coincident with the bottom edge of the tin dot, and its diameter in this unit is approximately 1 mil. The capacitance per unit area for *p-n* junctions formed by the same alloying techniques on the same *n*-type crystal wafer used in constructing the oscillator units has been found by S. Miller and D. Singer to be $3 \mu f/cm^2$, so that the

Figure 3 **Two views of the microwave oscillator mounted on conventional header.** *(Unit at left magnified 6.6 ×.)*



capacitance for this diode is approximately 20$\mu\mu$f. To produce resonance at 3000 Mc would require an inductance of 0.15 millimicrohenry, a value which is reasonable to expect for the loop inductance of the oscillator structure.* An estimate of the peak current of the Esaki diode *p-n* junction, based on measurements of the peak current per unit area of units similarly fabricated, is about 10 ma. Considering that the negative resistance region is thus limited to a few milliamperes of current and 100 millivolts of voltage, the rf power output of this oscillator is, at most, a few tens of microwatts. However, it is believed that improved fabrication techniques will allow higher powers in future models. The arsenic concentration in the *n*-type crystal has been measured by M. Nathan to be 1.4×10^{19} atoms/cc. The crystals and impurity dots were prepared by J. Marinace and the oscillators were fabricated by R. McGibbon.

The author acknowledges his appreciation to the above mentioned individuals and to the other members of the Semiconductor Research Department of the IBM Research Laboratory whose joint efforts have made the realization of a microwave semiconductor oscillator possible.

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*More recent models, with lower loop inductance, have oscillated as high as 4020 Mc. (Footnote added in proof.)

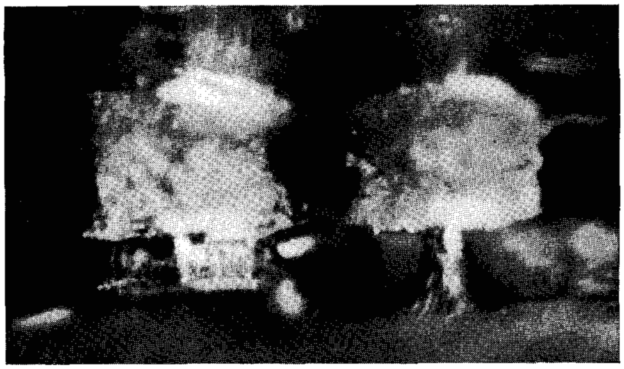

Figure 4 **Photomicrograph of the oscillator. The Esaki diode is the thin pedestal on the right (narrowest dimension about 1 mil).**

References

1. L. Esaki, "New Phenomenon in Narrow Ge P-N Junctions", *Phys. Rev.* **109,** 603 (1958).
2. H. S. Sommers, Jr. "Tunnel Diodes as High Frequency Devices", *Proc. of IRE* **47,** 1201 (1959).

This work was supported by the Department of Defense.

Received August 19, 1959