V. MICROWAVE AND MILLIMETER WAVE TECHNIQUES

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A. LOW-TEMPERATURE MILLIMETER WAVE RECEIVERS

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1. FREQUENCY-POWER FORMULAS FOR JOSEPHSON JUNCTIONS

Paul L. Penfield, Jr.

Russer[1] and Thompson[2] have derived (correctly) frequency-power formulas for lossless models of Josephson junctions. Each of these authors stated that his formulas are similar to the Manley-Rowe relations, but have additional terms for dc power.

It has previously been shown[3] that the Manley-Rowe equations apply in similar cases with dc power. My original motivation for this proof was to allow for power transmitted through rotating shafts, especially on synchronous and induction motors, but the derivation was general enough to include the present Josephson models. Recent results, therefore, should be regarded as a special case of the Manley-Rowe equations, rather than a new set of equations. Thompson stated explicitly his interpretation that the Josephson junction does not obey the Manley-Rowe equations; it is my belief that a more fruitful viewpoint is that with the dc power interpreted properly, the Josephson junction does obey the Manley-Rowe equations. This viewpoint makes it unnecessary to rederive other forms for the equations, such as would be necessary for subharmonic generation, or for excitation with more independent frequencies.

My early result[3] may be stated as follows. Consider a device with one or more ports through which power can pass. Each port has a pair of covariables. In this case there is only one port and the covariables are voltage and current. The Manley-Rowe equations are obeyed by any such device with an energy state function that (i) is a function of the integrals of one of the covariables from each port, and (ii) has as partial derivatives the other covariables. In this case the energy is a function of λ, the integral of voltage:

$$W(\lambda) = \int i \, d\lambda,$$

where

$$\lambda = \frac{\hbar}{2e}\,\phi,$$

with ϕ the superconducting phase, and

$$\frac{d\lambda}{dt} = v.$$

It is perfectly valid for the covariables to have nonzero average values, in which case the variables upon which the energy depends may be unbounded.

The resulting Manley-Rowe equations depend on the number of independent frequencies and the relationship of these to all frequencies at which power is exchanged. The general form is known, but the specific equations are different; for example, depending on whether subharmonics are present or there is synchronization. The equations are not altered by the presence of dc power, but the dc terms enter as if that power were exchanged at an ac frequency dictated by the unbounded variable on which the energy depends. In the case of a rotating machine, it is the angular frequency of the shaft, and in the case of the Josephson junction, the autonomous frequency.

Thompson also shows an equivalent circuit that has a parasitic loss element denoted G(v) to represent, among other things, tunneling electron current. A somewhat more accurate model[4] for this loss is a resistor whose value depends not upon the voltage but rather upon the superconducting phase, i.e., upon the integral of the voltage. Chua[5] has discussed this model, and given it the name "memristor." In particular, Chua has given the form of the frequency-power formulas for memristors, and they are different from the Manley-Rowe equations, and from the formulas for nonlinear resistors.

References

1. P. Russer, "General Energy Relations for Josephson Junctions," Proc. IEEE 59, 282-283 (1971).
2. F. D. Thompson, "Power Flow for Josephson Elements," IEEE Trans., Vol. ED-20, No. 8, pp. 680-683, August 1973.
3. Paul L. Penfield, Jr., Frequency-Power Formulas (The Technology Press of Massachusetts Institute of Technology, Cambridge, Mass., 1960), see Secs. 3.2 and 4.6.
4. B. T. Ulrich, Private communication, 1973.
5. L. O. Chua, "Memristor – The Missing Circuit Element," IEEE Trans., Vol. CT-18, No. 5, pp. 507-519, September 1971.

2. K-BAND GaAs SCHOTTKY-BARRIER DIODE MIXER

Robert W. Freund, Robert L. Kyhl

Experimental determinations of the mixing properties of a Schottky-barrier GaAs diode at K-band (~20 GHz), described in Quarterly Progress Report No. 112 (page 35), continue. The diode used in the K-band waveguide mixer assembly is a GaAs Schottky-barrier device obtained from the M. I. T. Lincoln Laboratory. Figure V-1 is a microscope photograph that clearly indicates the numerous "dot" sizes available on the $250\ \mu m \times 250\ \mu m \times 80\ \mu m$ semiconductor chip. Each "dot" is a gold layer 500 Å thick immediately above each platinum-gallium arsenide Schottky-barrier diode. Electrical contact is made by soldering the chip into the circuit and contacting one of the diode "dots" by means of an etched tungsten whisker as shown in Fig. V-2.

A ridged rectangular waveguide is used for the millimeter-wave circuitry. A portion of the ridge guide is shown in Fig. V-3. The semiconductor chip is soldered to the

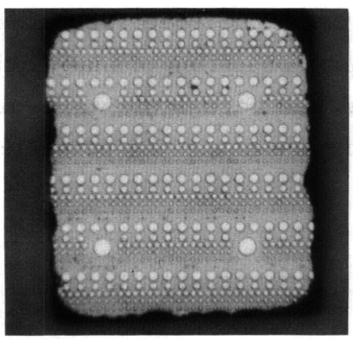

Fig. V-1. Various sizes of diode "dots" on a semiconductor chip.

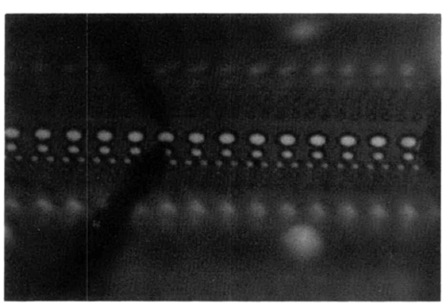

Fig. V-2. An etch whisker about to contact a 6 μm diode "dot."

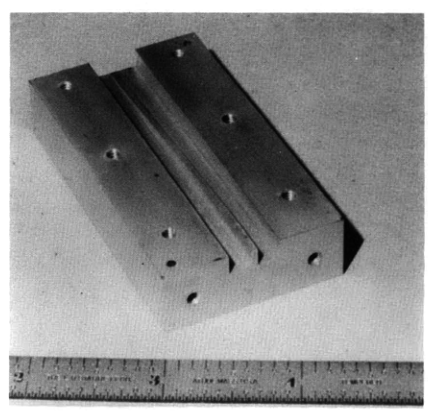

Fig. V-3. Bottom portion of the tapered section of the ridged waveguide mixer mount.

ridge approximately 8 mm ($\sim\lambda_g/4$ at these frequencies) from the front end (as viewed in the picture) and contacted by a whisker-post combination. The post passes through the IF choke section in the top portion of the mount.

Theoretical and experimental data are used to relate the different millimeter-wave properties to the actual waveguide mount. Measurement data of 1-MHz capacitance vs voltage permits the de-embedding of the diode from the rest of the waveguide structure. It has been assumed that the diode capacitance follows the familiar $c_o/\sqrt{1 - v/\Phi}$ law for abrupt junctions. The current-voltage measurements indicate a zero-bias capacitance of 24 fF (= 10^{-15} farad) and a barrier potential Φ of .86 volt. Current-voltage data for the forward conduction region indicate a consistent value of Φ and a dc spreading resistance R_s of 16 Ω. Millimeter wave measurements are continuing on this system at room temperature and will soon be undertaken at cryogenic temperatures.

3. 118-GHz MIXER DEVELOPMENT

Wesley G. Brodsky, David H. Staelin

The machined block for a mixer designed for use from 108 GHz to 128 GHz has been received and has been gold plated. In this block a "chip" consisting of many Schottky-barrier diodes must be mounted and a small wire positioned across the waveguide and contacted to a diode. Techniques for accomplishing this are now being perfected.