Correspondence

A Note on Tunnel Emission*

I would like to call attention to several errors in my recent communication.[1] In (1), the quantity between J_0 and the exponential should be squared, and there should be a 2 in the denominator of the expression for E_0. Also in the last equation for the figure of merit M, the E_0 in the numerator should be deleted and the E in the denominator should be changed to E_0.

It should be noted that these equations are very similar to those for ordinary field emission from the surface of a metal into a vacuum. However, the mechanism involved is somewhat different in principle. In the field emission case, electrons are confined by a region of classically forbidden energy, and are permitted to penetrate this region by virtue of their quantum mechanical properties. In contrast, the "forbidden" region considered in tunnel emission (or Zener breakdown) is itself a consequence of the wave nature of the electrons and the periodicity of the lattice. Because the amplitude of the wave function is attenuated similarly in both cases, the voltage-current expression for tunnel emission is essentially identical to the well-known Fowler-Nordheim expression for ordinary field emission when appropriate correction is made for the effective mass of the electron.

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* Received by the IRE, May 23, 1960.
[1] C. A. Mead, "The tunnel emission amplifier," Proc. IRE, vol. 48, p. 359: May, 1960.

Noise Performance of Tunnel-Diode Amplifiers*

The tunnel diode, first reported by Esaki,[1] is being considered for possible use as a low-noise amplifier[2,3] as well as for other applications.[4,5] For comparison of this amplifier with others, it is important to know the fundamental limit on noise performance.

A general way of obtaining the fundamental limit of amplifier noise performance has been given by Haus and Adler,[6] and this was simplified somewhat for negative-resistance amplifiers by this writer.[7] On this basis, we will calculate F, the lowest noise figure an amplifying system of high gain can have if it employs the tunnel diode and no other "better" amplifiers.

The tunnel diode can amplify because its volt-ampere characteristic shows a negative slope at some points. A typical curve is shown in Fig. 1, showing the dc operating point, and the product of the dc current I_0 and the magnitude of the negative resistance R.

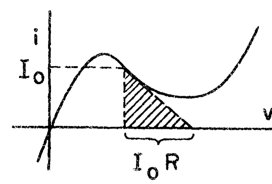

Fig. 1.

Sommers[4] has proposed the small-signal high-frequency equivalent circuit of Fig. 2. The negative resistance is $-R$, so that R is a positive quantity; C is the barrier capacitance; and R_s is the series resistance caused by lead resistance, bulk resistance of the semiconductor, and contact resistance. Fig. 3 shows the equivalent circuit with two noise generators: one to account for shot noise associated with the tunnelling process, represented by the current generator with mean-squared current

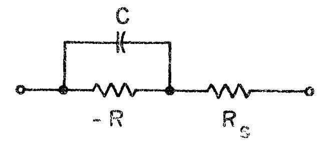

Fig. 2.

$$\overline{|i_n|^2} = 2qI_0\Delta f; \qquad (1)$$

and the other to represent thermal noise of the series resistance, with mean-squared voltage

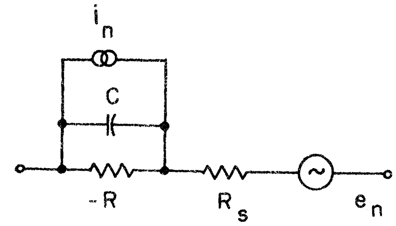

Fig. 3.

$$\overline{|e_n|^2} = 4kT_dR_s\Delta f \qquad (2)$$

where T_d is the diode temperature.

The best noise figure F is given by the formula[6,7]

$$F = 1 - \frac{\text{exchangeable noise power of the tunnel diode}}{kT_0\Delta f}. \qquad (3)$$

The exchangeable noise power is calculated from Fig. 3 to be

$$-\frac{\overline{|e_n|^2} + \overline{|i_n|^2}\dfrac{R^2}{1+(\omega RC)^2}}{4\left[\dfrac{R}{1+(\omega RC)^2} - R_s\right]} \qquad (4)$$

where ω is the operating frequency; so the fundamental limiting noise figure is

$$F = 1 + \frac{I_0R}{2kT_0/q}\,\frac{R}{R - R_s[1+(\omega RC)^2]} + \frac{T_d}{T_0}\,\frac{R_s}{\dfrac{R}{1+(\omega RC)^2} - R_s}. \qquad (5)$$

An interpretation of this formula is aided by consideration of some special cases.

Zero Series Resistance Limit

In the limit as $R_s \to 0$, F becomes

$$1 + \frac{I_0R}{2kT_0/q} \qquad (6)$$

which can be determined from Fig. 1, if the high-frequency value of R is the same as the dc value. The product I_0R is shown in Fig. 1, and F is merely one plus this value normalized to $2kT_0/q = 50$ mv. This model was used by Chang[2] to interpret experimental noise figures, but his numbers are somewhat higher than the limit given here because he 1) was not always operating with high exchangeable gain, 2) had extra loss in the circuit, and 3) included noise from the load.

Low-Frequency Limit

In the low-frequency limit the noise figure does not approach unity, but rather

$$1 + \frac{I_0R}{2kT_0/q}\,\frac{R}{R - R_s} + \frac{T_d}{T_0}\,\frac{R_s}{R - R_s}. \qquad (7)$$

Since low-noise amplifiers can be made at low frequencies, either with varactors or vacuum tubes, the tunnel diode will prob-

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[2] K. K. N. Chang, "Low-noise tunnel-diode amplifier," Proc. IRE, vol. 47, pp. 1268–1269; July, 1959.
[3] H. S. Sommers, Jr., K. K. N. Chang, H. Nelson, R. Steinhoff, and P. Schnitzler, "Tunnel diodes for low noise amplifications," 1959 WESCON Convention Record, pt. 3, pp. 3–8.
[4] H. S. Sommers, Jr., "Tunnel diodes as high-frequency devices," Proc. IRE, vol. 47, pp. 1201–1206; July, 1959.
[5] I. A. Lesk, N. Holonyak, Jr., U. S. Davidsohn, and M. W. Aarons, "Germanium and silicon tunnel diodes—design, operation, and application," 1959 WESCON Convention Record, pt. 3, pp. 9–31.
[6] H. A. Haus and R. B. Adler, "Circuit Theory of Linear Noisy Networks," Technology Press, Mass. Inst. Tech., Cambridge, Mass., and John Wiley and Sons, New York, N. Y.; 1959.
[7] P. Penfield, Jr., "Noise in negative-resistance amplifiers," IRE Trans. on Circuit Theory, vol. CT-7, pp. 166–170; June, 1960.