Correspondence

Theory of the Gunn Effect

Gunn [1] has recently discovered a new kind of current oscillations at microwave frequencies, in *n*-type GaAs and InP. In his paper, Gunn discusses several possible explanations for these oscillations. Most of these explanations he rejects outright; about the remainder he has serious reservations.

The purpose of this correspondence is to point out that most, if not all, of the known properties of the Gunn effect can be explained, at least qualitatively, if it is assumed that these semiconductors have a negative differential bulk conductivity above the oscillation threshold field and that the current oscillations are due to the periodic nucleation and disappearance of traveling space-charge instability domains, of the kind discussed by Ridley [2].[1]

Assume that the drift velocity vs field behavior is characterized by a negative differential mobility range as in Fig. 1. Ridley [2] has shown that a crystal cannot be biased stably in that range but that it will break up into domains of lower and higher fields, corresponding to the points L and V in Fig. 1, and that these domains will travel with a velocity equal to the drift velocity v_L of the carriers. As one high-field domain moves out of the crystal at the positive electrode a new domain gets nucleated at or near the negative end. In sufficiently short samples only one nucleation center will be active, leading to coherent oscillations, with a frequency approximately equal to v_L/L, where L is the sample length. A detailed investigation [3] shows that the frequency is somewhat larger than this value and that it increases slowly with increasing voltage, in agreement with Gunn's observations.

The terminal current associated with such domain travel oscillates between the values corresponding to the valley velocity and to the threshold value, also in agreement with the observations, if one assigns Gunn's low current limits to the valley drift velocity.

Such a field-controlled bulk-type negative conductance cannot be stabilized by loading it with a sufficiently low impedance, in contrast to the interface-type negative conductance of a single Esaki tunnel diode. It behaves essentially like a large number of series-connected tunnel diodes. This is in agreement with Gunn's observation that it is impossible to stabilize the current at the low value.

According to Ridley's simple model the domains, and thereby the oscillations, should disappear if fields in excess of the valley field are applied. However, Ridley's model does not take into account the fact that, even in this case, the field must pass

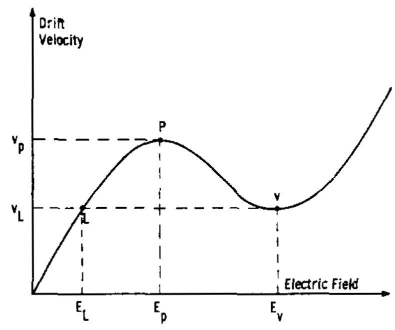

Fig. 1.

through the negative mobility range for a finite distance, near the electrodes. As Shockley [4] has pointed out, such an oversimplified treatment of the boundary conditions may lead to profound errors in problems of this sort. Some form of instability is, therefore, likely to remain in these high-field cases, although it is not likely to have the form of strong coherent transit-time oscillations. All of this is consistent with the work of Day [5] of this laboratory, who succeeded in strongly attenuating existing oscillations by increasing the field strength.

Another refinement necessary in Ridley's model is the fact that space-charge limitations prevent the domain walls from being arbitrarily thin, particularly at the electron-depleted positive end of the high-field domain, where the space-charge density cannot exceed the donor space charge. For a sufficiently low net donor density the domain wall thickness exceeds the sample length and no domains are possible. If one assumes a difference between low and high fields of a few thousand volts per cm, this occurs when the product of net donor density and sample length is less than a few times 10^{10} cm^{-2}. This was also observed by Day [5].

We wish to suggest that the origin of the negative differential mobility is Ridley and Watkins' mechanism [6] of electron transfer into the satellite valleys that occur in the conduction bands of both GaAs and InP. Gunn [1] has rejected this mechanism on the grounds that the energy separation of the satellite valleys would require electron temperatures of the order of 4000°K, while the experimental electron temperature at 80 per cent of the threshold field is only of the order of 400°K. However, this argument overlooks the fact that the combined density of states of the six (100) satellite valleys is about 400 times that of the main valley [7]. Hilsum [8] has considered this fact and has estimated a velocity peak field of 3000 v/cm, an electron temperature at this field of only about 670°K, and of only about 530°K at 80 per cent of the peak field, all values for the already high lattice temperature of 373°K, with lower values for lower temperatures.

Such drastic changes in electron distribution are, of course, not instantaneous in either time or space. This indicates a third necessary modification of Ridley's model. The details of such rate limitations have not been worked out but one consequence that can be readily predicted is that the threshold field will increase with decreasing sample length, in order to accomplish the distribution change along the shorter available distance. This dependence, too, has been observed.

HERBERT KROEMER
Varian Associates
Palo Alto, Calif.

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[1] Ridley himself hints at this possibility in "Electric bubbles and the quest for negative resistance," *New Scientist*, vol. 22, pp. 352–355; May, 1964.

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RF Characteristics of Thin Dipoles

In the above paper [1] Mack and Reiffen give an analysis of scattering by dipoles which is fundamentally in error, although their results are approximately correct. It is the purpose of this communication to call attention to the correct formulation, and to show to what extent the formulas of Mack and Reiffen apply.

The error lies in the identification of power "dissipated" in a Thevenin equivalent circuit with reradiated power. A little thought shows that this cannot generally be true, since an open-circuited antenna would then scatter no field. Also what justification would one have for using the Thevenin equivalent over the Norton equivalent? This would give diametrically opposite predictions as to reradiated power. In general, no identification of a power dissipated in an equivalent circuit can be made.

The correct formulation for scattering by antennas was first given by Y. Y. Hu for center-loaded dipoles [2], and this was later generalized to arbitrary antennas [3], [4]. The exact formulation for an antenna loaded by an impedance Z_L yields an echo area [4].

$$\frac{\sigma}{\lambda^2} = \frac{1}{\pi}\left| \Delta Z_o' - \frac{Z_{oa}' Z_{ao}'}{Z_a + Z_L} \right|^2 \qquad (1)$$

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