Letters to the Editor

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Proposed Negative-Mass Microwave Amplifier

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AT high kinetic energies, electrons and holes in semiconductors have negative effective masses. In an electric field the current contribution from negative-mass carriers is opposite to the electric field, and a semiconductor containing a sufficient number of such carriers would have a negative resistance. It could thus be used as an active element in an oscillator or amplifier,[1] up to frequencies of the order of the reciprocal collision time of the carriers, i.e., up to about 1000 kMc/sec.

Any attempt to accelerate normal carriers up into the negative-mass energy range faces the difficulty that optical-phonon scattering and avalanche ionization will, in most cases, prevent the carriers from reaching that range.

We want to point out that negative masses occur at energies close to the band edge if the energy contours are re-entrant there, as is the case, for example, for the heavy holes in germanium. There, the energy contours are re-entrant along the six [100] directions of k space[2] (Fig. 1). Along these directions, then, the *transverse* effective masses are negative, i.e., along the k_x axis,

$$m_y=\hbar^2\Big/\frac{\partial^2\epsilon}{\partial k_y{}^2}=m_z=\hbar^2\Big/\frac{\partial^2\epsilon}{\partial k_z{}^2}<0.$$

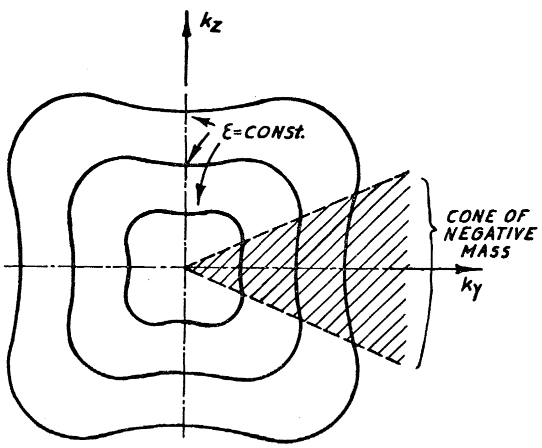

FIG. 1. Schematic energy contours for heavy holes in Ge.

From the data of reference 2, one calculates

$$m_y=m_z\approx-0.3m_0$$

for germanium.

A microwave amplifier, therefore, is proposed, consisting of a p-type Ge crystal with a strong dc bias field, applied in the [100] direction, and the electrical rf field of a resonant cavity or a wave guide perpendicular to it; the bias field shifts the total hole population away from $k=0$ and toward the inside of the conical region of negative transverse mass. The rf field will then be amplified if the majority of the holes are brought inside this cone.

In order to make this possible, scattering of the holes out of the negative-mass cone must be avoided. A totally inelastic type of scattering is desirable where the holes after each collision return to nearly $k=0$. If the collision cross section is large enough, optical phonon scattering is of this type. Shockley's interpretation[3] of the high-field mobility data[4] in Ge suggests that this might be the case in Ge at biasing fields of a few thousand volts/cm.

This amplifier principle is not restricted to germanium, but should hold for all semiconductors with re-entrant energy contours and high optical-phonon cross sections, such as p-type Si and III–V compounds.

The detailed theory will be presented elsewhere shortly.

Note added in proof.—Preliminary experiments with Ge have not shown the effect. This is interpreted as being the result of Ge's not having a high enough scattering cross section, which is likely because the two atoms per unit cell are identical. Experiments on compounds have not been performed yet.

That space-charge instabilities caused by the negative dc conductivity can be avoided, and how, will be shown with the detailed theory.

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Penetration of Magnetic Fields through Superconducting Films

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BARDEEN, Cooper, and Schrieffer[1] have recently formulated a molecular theory of superconductivity. Their analysis leads to a nonlocal relation between current and field not very different from that