tory component of the transverse magnetoresistance for H parallel to $\vec{b}_3$. Note the presence of the small secondary oscillations which occur on the left-hand slope of each of the major oscillations. These small oscillations have a constant phase relationship with the major ones. According to the foregoing treatment each minimum in the magnetoresistance must correspond to a maximum in the transmission probability. Thus each of the minima on either side of the small oscillation must correspond to a quantum level being at the Fermi energy. Hence the small oscillations must result from spin splitting of the original Landau levels. If each of the Landau levels is split into two levels by magnetic interactions, the effective energy gap E_g' will contain a secondary oscillation associated with the spin splitting which will be exhibited in the transverse magnetoresistance as a secondary oscillation of the type seen in Fig. 4. We estimated the effective g factor for the electrons on the needle from the separation of the two subsidiary minima and obtained a value of $g=34$. While effective g values of this magnitude have been observed previously in semiconductors and semimetals, none have been observed, to our knowledge, which differed appreciably from a value of 2 in any metal with a large number of conduction electrons. It is of interest to note that the effective g value of the needle portion of the Fermi surface cannot be measured by a normal spin-resonance technique, since the needle contains only a very minor portion of the conduction electrons in zinc, while the spin-resonance technique measures the effective g values of the predominant carriers.

I would like to thank Dr. W. L. Gordon, Dr. T. G. Eck, and Dr. J. R. Reitz for many interesting and informative discussions.

*Work supported by the Air Force Office of Scientific Research.

[1]C. A. Renton, Proceedings of the Seventh International Conference on Low-Temperature Physics, edited by G. M. Graham and A. C. Hallett (University of Toronto, Canada, 1961), p. 216.

[2]M. G. Priestley, Proceedings of the Seventh International Conference on Low-Temperature Physics, edited by G. M. Graham and A. C. Hallett (University of Toronto Press, Toronto, Canada, 1961), p. 230.

[3]M. H. Cohen and L. M. Falicov, Phys. Rev. Letters 7, 231 (1961).

[4]R. W. Stark, T. G. Eck, W. L. Gordon, and F. Moazed, Phys. Rev. Letters 8, 360 (1962).

[5]A. S. Joseph and W. L. Gordon, Phys. Rev. 126, 489 (1962).

[6]D. F. Gibbons and L. M. Falicov (to be published).

[7]W. A. Harrison, Phys. Rev. 118, 1190 (1960).

[8]M. H. Cohen and L. M. Falicov, Phys. Rev. Letters 5, 544 (1960).

SOME OBSERVATIONS OF GROWING OSCILLATIONS IN ELECTRON-HOLE PLASMA

Betsy Ancker-Johnson
Boeing Scientific Research Laboratories, Seattle, Washington
(Received October 11, 1962)

Highly reproducible growing oscillations have been observed in electron-hole plasma. The plasma is produced by injection[1] from current contacts into single-crystal p-type indium antimonide at 77°K. The circuit consists simply of an essentially constant-current source (pulsed) and a 10-ohm resistor in series with the sample to allow determination of the current through it. Since the pulse lengths are short (~10^{-6} sec) and the repetition rate low (<1 $\sec^{-1}$), the temperature of the sample increases by less than 10^{-1} °K. Side contacts on the crystal are used to observe voltage behavior. The sample dimensions are $(0.75\pm0.03)\times(0.75\pm0.03)\times12$ mm with contacts soldered as shown in Fig. 1.

Two types of growing oscillations have been observed: For one type, observed in sample No. A, the frequency is current controlled and for the

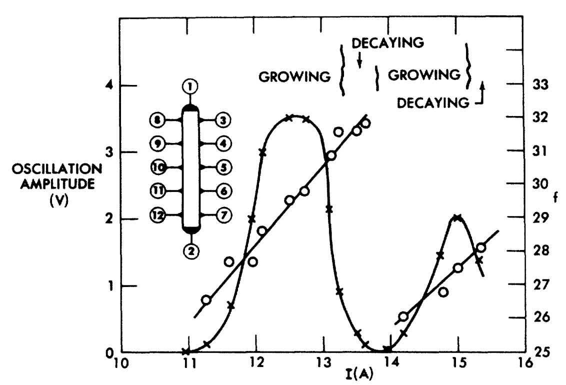


FIG. 1. The full amplitude of oscillation at maximum and the frequency plotted as functions of the current. The currents at which growing oscillations occur are indicated. Basic properties of this sample (No. A) are $p_0=5.5\times10^{15}$ cm^{-3}, $\sigma=4.5$ (ohm-cm)$^{-1}$, and μ_p $=6300$ cm^2/V-sec.

other, observed in sample No. B, the frequency is independent of current. Both occur in the absence of an applied magnetic field, in contrast to helical-instability oscillations (oscillistor).

Those oscillations whose frequency is controlled by the current magnitude occur only at currents greater than that required for the onset of self-pinching[2-5] in the plasma. At threshold these oscillations grow in time. As the current is increased, the nature of the oscillations cycles between decaying and growing, as indicated in Fig. 1. An example of these growing oscillations is shown in Fig. 2 which is an oscilloscope trace of the voltage observed between contacts 4 and 5. The amplitude vs time plotted on semilog paper yields a region which is linear over at least nine cycles of oscillation. An exponential growth time may thus be defined as the time required for the amplitude to increase by a factor of $e = 2.71\cdots$ using extrapolation where necessary. For the example shown in Fig. 2 this growth time is 0.6 μsec.

The dependence of the amplitude, as observed by the potential difference, and the frequency of oscillation on the current magnitude are shown in Fig. 1. The frequency is linear with current until the growing oscillations become decaying ones with negligible amplitude. Then a second mode is observed with a threshold of ~14 A. Again the frequency is approximately linear with current. The growth time is essentially constant at 0.6 μsec as a function of current while the amplitude is increasing. Then the growth time increases, e.g., to 1.1 μsec at 13.1 A, until decaying oscillations of very small amplitude appear (Fig. 1).

The type of growing oscillation whose frequency is independent of current has much greater oscillation amplitudes (Figs. 3 and 4). The threshold for oscillation occurs at currents much less than the critical current for pinching and, in fact, at

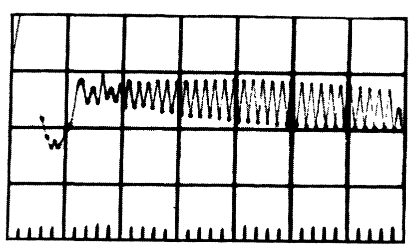


FIG. 2. Oscillogram of the voltage between contacts 4 and 5 with a current of 12.8 A passing through the full length of the sample. The ordinate is 5 V/large division, and the abscissa is 0.2 μsec/large division. A repetition of three pulses was used to produce the photograph.

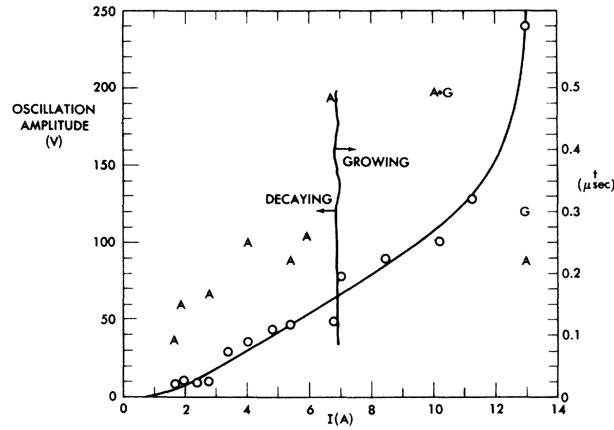


FIG. 3. The full amplitude of oscillation at maximum, and the growth and attenuation times plotted as functions of current. "A" indicates attenuation time, "G," growth time. The plasma was injected from contacts +9 and -12; the voltage contacts were 5 and 6. Basic properties of this sample (No. B) are $p_0 = 7.1 \times 10^{14}$ cm^{-3}, $\sigma = 0.66$ (ohm-cm)$^{-1}$, and $\mu_p = 5800$ cm^2/V-sec.

plasma currents, $I_{\text{plasma}} = I_{\text{total}} - I_{\text{Ohmic}}$, whose magnitude is only about twice the Ohmic current. However, until the current has a magnitude of somewhat more than twice the critical current for

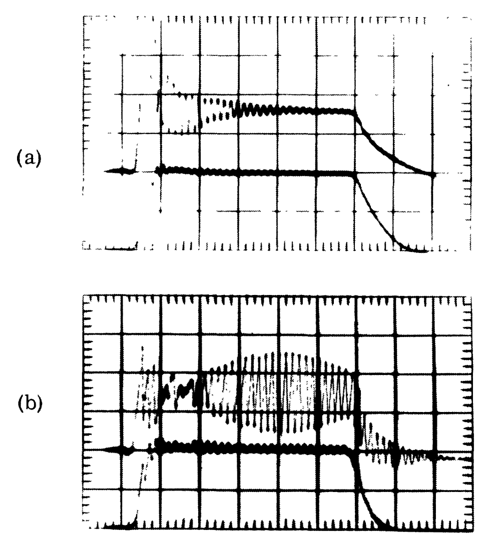


FIG. 4. Oscillograms illustrating (a) decaying oscillations and (b) growing ones. The lower traces represent the current and the voltage contacts are as in Fig. 3. The abscissa is 0.2 μsec/large division. The ordinate for the voltage is (a) 10 V/large division and (b) 50 V/large division. The current is (a) 4.0 A and (b) 10.25 A. Each exposure is for the duration of three pulses. Note in (a) that the rise in voltage after the sharp drop caused by carrier injection is typical for the occurrence of pinching.

pinching, the oscillations exhibit no growth [Fig. 4(a)]. Their attenuation times are exponential and increase with current until growing oscillations occur (Fig. 3). Their amplitude also increases with current (Fig. 3), whereas the frequency remains constant at 30.8 ± 0.2 Mc/sec.

Further increase in current beyond ~7 A produces oscillations that grow in time and then decay [Fig. 4(b)]. A semilog plot of the amplitude A vs time t yields the curve $A = \text{sech}t$ from which exponential growth and decay times are deduced. The oscillations of Fig. 4(b) have symmetric growth and attenuation times which are 0.49 μsec. At 13.0 A, as noted in Fig. 3, the growth and attenuation times are somewhat different. The amplitude of the growing oscillations increases very rapidly with current to extremely large values, even larger than the potential difference.

The frequency remains constant over the entire range of current for which either decaying or growing oscillations are observed. The frequency does not change when different contacts are used for the injection of the plasma, nor is it influenced by shunting the sample with either a 50-ohm resistance or a 10^{-9}-F capacitance.

The behavior of both types of growing oscillations in the presence of magnetic fields will be discussed elsewhere.

All the conditions necessary for producing either of these two types of growing oscillations are not known as yet, nor is it understood why a particular type occurs in a particular sample, but when either is observed its behavior is highly reproducible. It seems probable that the constant-frequency growing oscillations are related to acoustic electron waves.

[1]B. Ancker-Johnson, R. W. Cohen, and M. Glicksman, Phys. Rev. 124, 1745 (1961).

[2]M. Glicksman and M. C. Steele, Phys. Rev. Letters 2, 461 (1959).

[3]M. Glicksman and R. A. Powlus, Phys. Rev. 121, 1659 (1961).

[4]A. G. Chynoweth and A. A. Murray, Phys. Rev. 123, 515 (1961).

[5]B. Ancker-Johnson and R. W. Cohen, Bull. Am. Phys. Soc. 6, 311 (1961). In this paper, as well as in references 1 and 3, very small amplitude oscillations during pinching were observed. Although these oscillations sometimes had long attenuation times, growing oscillations were not reported. It was noted in both references 1 and 3 that the oscillation frequency increased with current but no dependency reported.

EXPERIMENTAL DETERMINATION OF EFFECTIVE MASSES IN A BISMUTH-ANTIMONY ALLOY

G. E. Smith
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received November 2, 1962)

Hybrid and "tilted-orbit" cyclotron resonance has been observed in an alloy consisting of 5 atomic percent antimony in bismuth. Such resonances have previously been studied in pure bismuth[1] and proved to be an effective means of determining effective masses. It is found in the present work that in $Bi_{95}Sb_5$, the electron effective masses are smaller by about a factor of two than those measured in pure bismuth, and the hole masses are essentially unchanged.

A model of the band structure of bismuth-antimony alloys has been derived by Jain[2] from galvanomagnetic studies by assuming that the band structure changes continuously from that of pure bismuth with the addition of antimony. According to Jain's model, the addition of antimony reduces the band overlap E_0 but does not change effective masses or the energy gap E_g between the conduction band and the next lower band. Measurements of the de Haas–van Alphen effect[3] in the 0-1 wt.% range show no change in effective mass.

The experiment reported here was performed on material grown by the zone-leveling technique described elsewhere.[4] A sample was cut with the bisectrix axis perpendicular to the surface. Linearly polarized microwaves ($\nu = 70$ kMc/sec) were used with the electric field oriented along either the binary or trigonal axis. The magnetic field was in the plane of the sample and could be rotated either parallel or perpendicular to the microwave E field. The measurements were carried out at 1.3°K and the absorbed microwave power was measured by a calorimetric method.[1] Experimental plots of absorption coefficient vs magnetic field are shown in Figs. 1 and 2.

The model for the band structure was assumed to have the same form as that for pure bismuth. This model consists of three electron ellipsoids, one of which is given by

$$E_e = (\hbar^2/2m_0)(\alpha_{11}k_1^2 + \alpha_{22}k_2^2 + \alpha_{33}k_3^2 + 2\alpha_{23}k_2k_3), \quad (1)$$

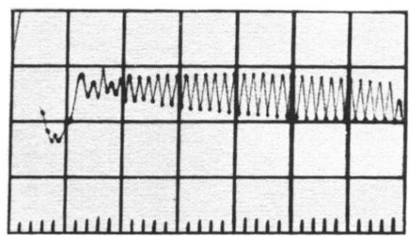
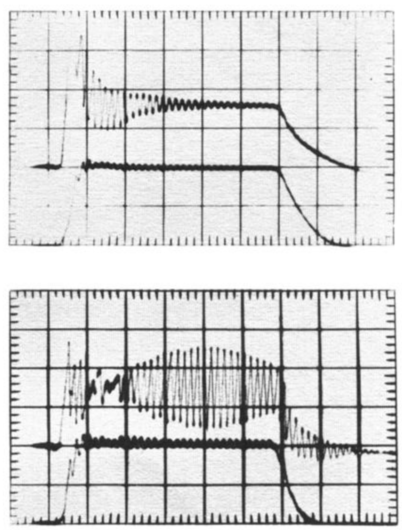


FIG. 2. Oscillogram of the voltage between contacts 4 and 5 with a current of 12.8 A passing through the full length of the sample. The ordinate is 5 V/large division, and the abscissa is 0.2 μsec/large division. A repetition of three pulses was used to produce the photograph.



(a)

(b)

FIG. 4. Oscillograms illustrating (a) decaying oscillations and (b) growing ones. The lower traces represent the current and the voltage contacts are as in Fig. 3. The abscissa is 0.2 μsec/large division. The ordinate for the voltage is (a) 10 V/large division and (b) 50 V/large division. The current is (a) 4.0 A and (b) 10.25 A. Each exposure is for the duration of three pulses. Note in (a) that the rise in voltage after the sharp drop caused by carrier injection is typical for the occurrence of pinching.