A measurement of the minimum in C_{sc} at zero current locates the minimum in R_1 and thus the optimum field.

For other semiconductors or germanium at other temperatures the dielectric constant κ and the intrinsic carrier concentration n_i will be different. Figures 1 and 2 can still be used with the following scale changes:

$$R_1(\kappa,n_i,T)=R_1(\text{Ge, } 300°\text{K})\times(1.38\times10^{-5})\times(n_i/\kappa T)^{1/2},$$

$$\mathcal{E}_s(\kappa,n_i,T)=\mathcal{E}_s(\text{Ge, } 300°\text{K})\times(4.63\times10^{-8})\times(n_iT/\kappa)^{1/2},$$

where $\kappa=16$ and $n_i=2.5\times10^{13}/\text{cm}^3$ for Ge at $T=300°$K.

ACKNOWLEDGMENT

We would like to thank Dr. Stephen Jasperson for several helpful discussions.

PHYSICAL REVIEW VOLUME 187, NUMBER 3 15 NOVEMBER 1969

de Haas–van Alphen Effect in $AuGa_2$

J. T. LONGO*† AND P. A. SCHROEDER*‡
Physics Department, Michigan State University, East Lansing, Michigan 48823

AND

M. SPRINGFORD§ AND J. R. STOCKTON
School of Mathematical and Physical Sciences, University of Sussex, England

(Received 6 June 1969)

New de Haas–van Alphen data on the metallic fluorite compounds $AuGa_2$ and $AuIn_2$ are presented. Several new frequency branches have been observed, including two in $AuGa_2$, which are tentatively ascribed to electrons in the fifth zone. The results are in general agreement with recent theoretical calculations by Switendick, which predict that the second zone is full in $AuGa_2$.

IN what has recently been termed "the $AuGa_2$ dilemma"[1] it has been observed that, of the three metallic compounds $AuAl_2$, $AuGa_2$, and $AuIn_2$, which have the fluorite structure, $AuGa_2$ shows anomalous properties in the magnetic susceptibility, Knight shifts, nuclear spin-lattice relaxation rate, and thermoelectric power,[2] whereas the de Haas–van Alphen (dHvA) results[3] to date show a remarkable similarity between the three Fermi surfaces and the nearly free-electron (NFE) model. More recently, superconducting critical points, heat capacities, and magnetic susceptibilities of $AuGa_2$ and its dilute alloys with palladium have been studied,[4] and further measurements on nuclear-magnetic-resonance measurements have been performed.[5] Switendick[5,6] has performed augmented-plane-wave calculations of the band structure of these compounds and has proposed that some of the above anomalous properties may be related to his result that, of the above three compounds, the second band is full only in $AuGa_2$.

In this note we present new dHvA data observed in high-resistance-ratio ($\sim$700) $AuGa_2$ crystals using high (up to 95 kG) magnetic fields. Previous dHvA data are confirmed, and the new data are consistent with the interpretation that in $AuGa_2$ the second band is fully occupied at 4.2°K. Furthermore, there is strong evidence for the existence of a fifth-zone surface which is predicted by Switendick's calculations.[6]

In Fig. 1, we show the third and fourth zones of the (NFE) model,[3] along with the extremal cross sections in the principal crystallographic directions. In Fig. 2, we show the experimental results for H in the (110), for the areas of the smaller extremal orbits, and in Fig. 3, results for all orbits in (100) and (110) compared with the results of Stafleu and van't Hof-Grootenboer[7] for $AuIn_2$ for a sample with a much lower residual resistance ratio. Areas are measured in terms of $(2\pi/a)^2$ throughout, where a is the lattice parameter. We have assigned areas to orbits according to the NFE labels in Fig. 1. In addition to results which confirm those of Jan *et al.*,[3] we present the following new data: (a) the assigned arms B_3, B_4, C_3'', and A_3, which confirm the essential one-to-

* Work supported in part by the National Science Foundation.
† Present address: North American Rockwell Science Center, Thousand Oaks, Calif.
‡ Guest scientist at University of Sussex, England.
§ Work supported by the Science Research Council.
[1] V. Jaccarino, M. Weger, J. H. Wernick, and A. Menth, Phys. Rev. Letters **21**, 1811 (1968).
[2] J. P. Jan and W. B. Pearson, Phil. Mag. **8**, 279 (1963).
[3] J. P. Jan, W. B. Pearson, Y. Saito, M. Springford, and I. Templeton, Phil. Mag. **12**, 1271 (1965).
[4] A. Menth, J. H. Wernick, T. H. Geballe, G. Hall, and J. P. Maita, Bull. Am. Phys. Soc. **14**, 382 (1969).
[5] A. C. Switendick and A. Narath, Phys. Rev. Letters **22**, 1423 (1969).
[6] A. C. Switendick, Bull. Am. Phys. Soc. **14**, 360 (1969).
[7] M. D. Stafleu and A. E. van't Hof-Grootenboer, in *Proceedings of the Eleventh Conference on Low Temperature Physics, St. Andrews, Scotland, 1968*, edited by J. F. Allen, D. M. Finlayson, and D. M. McCall (University of St. Andrews Printing Dept., St. Andrews, Scotland, 1969), Vol. 2, p. 1133.

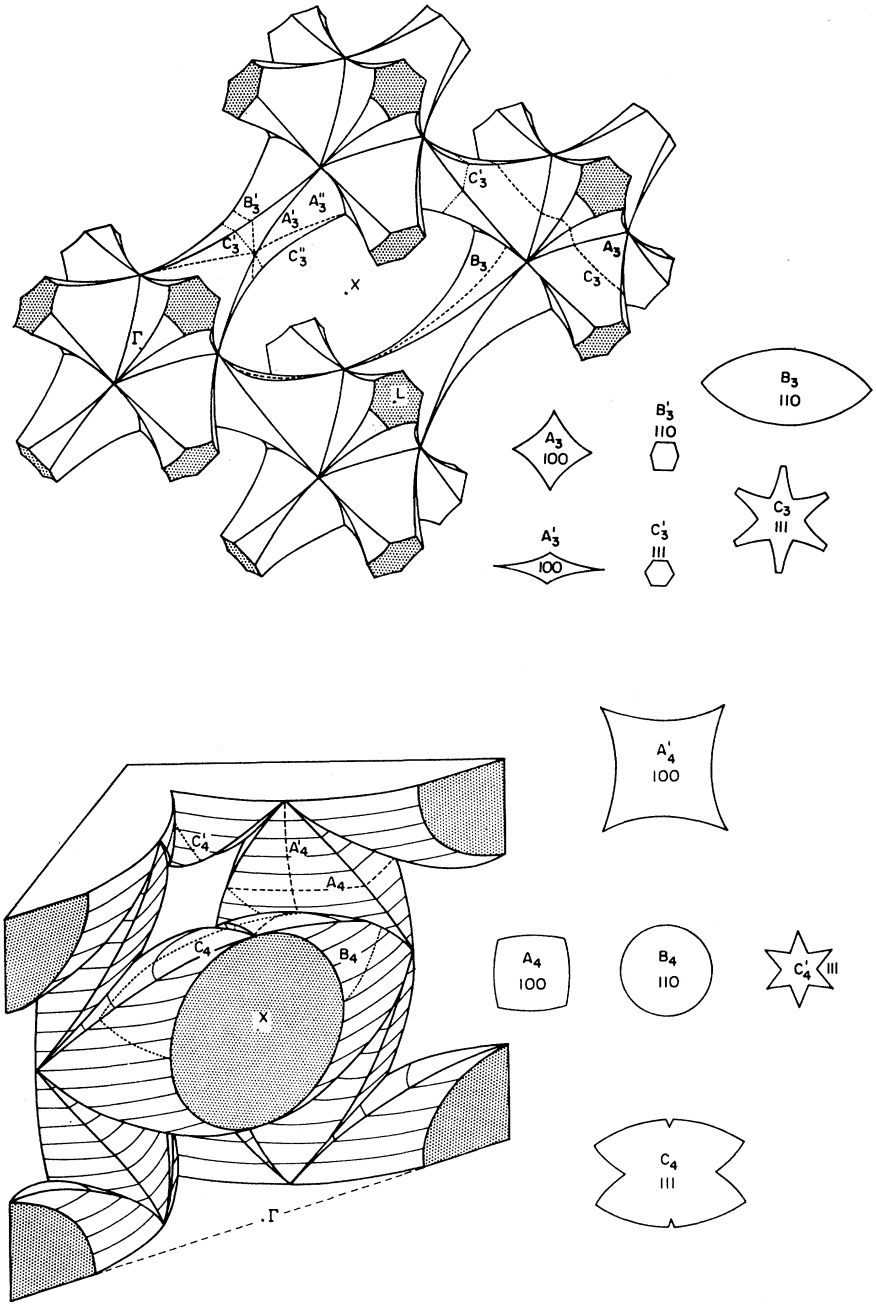

FIG. 1. NFE Fermi surfaces and extremal areas of the Fermi surfaces of $AuAl_2$, $AuGa_2$, and $AuIn_2$. The upper diagram is the third zone (holes) and the lower the fourth zone (electrons).

one relationship between observed and NFE orbits; (b) the nonassigned arms labeled A_x and Q; and (c) the double frequency in the vicinity of A_4.

Frequencies close to that expected for the NFE A_4' orbit have been observed, but they are so closely harmonics of the lower arm marked A_4 that a positive identification is not possible. Jan *et al.*[3] observed a similar relationship in $AuAl_2$. On the other hand, there is strong evidence that the frequencies corresponding to areas $\sim$0.6 units can be resolved into two distinct branches. It is not clear how these should be assigned, but it is most unlikely that the upper one is the A_4' branch. Frequencies (A_x) corresponding to areas $\sim$0.06–0.1 unit have been observed close to $\langle 100 \rangle$ in one run only. This and the quite definite low-area branch Q between $\langle 100 \rangle$ and $\langle 111 \rangle$ we tentatively ascribe to the fifth zone.

In $\langle 111 \rangle$ a wide band of frequencies occurs near the NFE singular orbit C_3''. From high-field Hall-effect measurements[8] we expect the electron orbit C_4 to be replaced by a hole orbit C_4'' of approximately equal area. We also expect that the B_4-C_4 branch will no

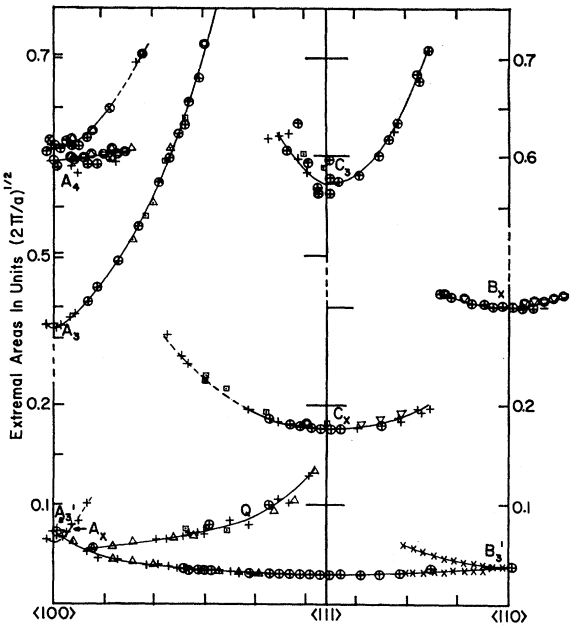

FIG. 2. dHvA results for the extremal cross sections of the Fermi surface of $AuGa_2$ for H in (110). The different symbols for experimental points correspond to different runs. The circled points are those with very strong signals. Branches of weak signals which require further confirmation are shown by broken lines. Areas in the principal directions are labeled according to the nomenclature in Fig. 1.

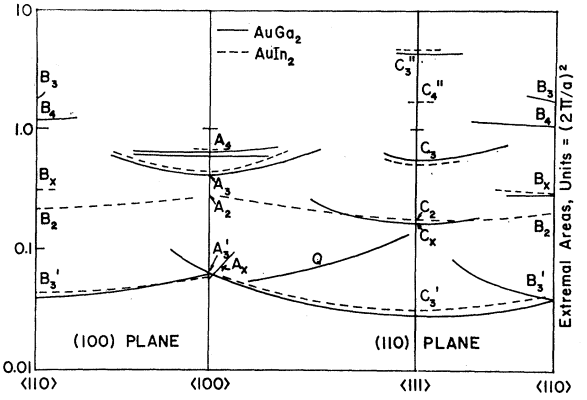

FIG. 3. Comparison of the extremal areas obtained by dHvA measurements in $AuGa_2$ (present work) and $AuIn_2$ (Ref. 7) for H in (100) and (110). C_3'' and C_4'' measurements in $AuIn_2$ are by present authors.

longer be the continuous branch expected from the NFE model. The latter certainly agrees with experiment, but no area corresponding to the hole (C_4'') or electron orbit C_4 has been observed.

We confirm the result of Jan *et al.*[3] that in $AuGa_2$ there is no continuous branch across (110) corresponding to a small closed second-zone surface. If we accept Switendick's[5,6] result that the second zone is full, we are faced with the following possibilities in the assignment of the branch labeled C_x (Fig. 2) centered on ⟨111⟩ with area ~0.18 units and B_x centered on ⟨110⟩ with area ~0.3 units:

(1) The dHvA signal in $AuIn_2$ corresponding to B_x has been ascribed to B_4.[7] However, considering the remarkable similarity of the results for $AuGa_2$ and $AuIn_2$ shown in Fig. 3, it is very likely that branches at ~1.1 and 1.8 units will be found for $AuIn_2$ when measurements are performed at higher fields in better crystals of this material. The branch at 1.1 units seems to be the better candidate for B_4.

(2) C_x might be assigned to C_4' and B_x to the fifth zone. C_4' has not been observed in $AuIn_2$ or $AuAl_2$. This may not be surprising as far as $AuIn_2$ is concerned: if C_x is assigned to C_4', it is probable that the C_4' branch for $AuIn_2$ will be very close to C_x, and, therefore, from Fig. 3 it should lie almost on top of the $AuIn_2$ second-zone curve. Opposed to this assignment is the fact that C_x and B_x have certain properties which suggest they are part of the same sheet; B_x is a branch with very strong signals and it ceases abruptly as H moves from ⟨110⟩ towards ⟨111⟩ in (110) and the rather weaker arm C_x appears very close to the same field direction.

(3) C_x and B_x both belong to the same sheet, presumably the fifth zone if we agree with Switendick that the second zone is full. The similarity of the B_x branches in $AuGa_2$ and $AuIn_2$ and the fact that $AuIn_2$ has already had a branch assigned to the second zone provide strong evidence that B_x is not associated with a nonfilled second zone.

Preliminary measurements on $AuIn_2$ by the present authors show that both the C_3'' and C_4'' branches are present in $AuIn_2$. These branches are also observed in $AuAl_2$ by Jan *et al.*[3] No B_x branch nor any others corresponding with the possible fifth-zone arms for $AuGa_2$ mentioned above have been observed yet in $AuAl_2$.

We conclude that there is significant evidence for the existence of the fifth zone in $AuGa_2$ and that there are distinct differences between the lower-frequency measurements on the three compounds which could be associated with the second band being full in $AuGa_2$ only. As yet, however, the assignment of the lower-frequency branches cannot be made with certainty. Finally, we note the remarkable similarity of the $AuGa_2$ and $AuIn_2$ results, which is consistent with the similarity of the high-field Hall-effect data for these materials.[8]

[8] J. Longo, P. A. Schroeder, and D. Sellmyer, Phys. Rev. **182**, 658 (1969).