critical point.

[14]In principle, Eqs. (1a)–(1c) should be applicable *all along* the *second*-order line provided the constants $A$, $B$, $C$, and $D$ are made suitably $H$ dependent, and $\lambda$ is appropriately modified. That our theory requires only three exponents to describe second-order and tricritical behavior (instead of a possible five as in general scaling theory, Refs. 5 and 6) appears to be a result of both our choice of scaling variables (note that $\lambda$ does not couple to the transition through $r$) and of our simple choice for $\psi$.

[15]D. M. Saul and M. Wortis, in *Magnetism and Magnetic Materials–1971*, AIP Conference Proceedings No. 5, edited by C. D. Graham, Jr., and J. J. Rhyne (American Institute of Physics, New York, 1972), p. 349.

[16]Blume, Emery, and Griffiths, Ref. 9.

[17]The notation employed is that of Ref. 16.

[18]C. W. Garland and B. B. Weiner, Phys. Rev. B 3, 1634 (1971).

[19]E. H. Graf, D. M. Lee, and J. D. Reppy, Phys. Rev. Lett. 19, 417 (1967).

[20]G. Goellner and H. Meyer, Phys. Rev. Lett. 26, 1534 (1971).

[21]B. B. Weiner and C. W. Garland, to be published.

[22]W. Yelon and D. E. Cox, private communication.

[23]F. Harbus and H. E. Stanley, Phys. Rev. Lett. 29, 58 (1972).

[24]T. Alvesalo *et al.*, Phys. Rev. A 4, 2354 (1971).

# Metal-like Plasma Resonance in Fast-Neutron-Irradiated GaAs Observed by Means of Electroreflectance

T. O. Tuomi and O. J. A. Tiainen*

*Helsinki University of Technology and Technical Research Centre of Finland, SF-02150 Otaniemi, Finland*

(Received 13 October 1972)

The metallic zones induced by reactor fast neutrons in GaAs were studied. The samples were irradiated at 300 to 310 K and the electroreflectance spectrum of the samples was measured before irradiation and after several irradiation periods. After irradiation up to a fast-neutron fluence of about $7\times10^{16}$ $n/\mathrm{cm}^2$ a new electroreflectance peak at 1.33 eV was observed. The appearance of this peak can be explained with a metal-like plasma resonance suggested by McNichols, Hayes, and Ginell.

The absorption measurements on GaAs irradiated up to a fluence of $6\times10^{16}$ $n/\mathrm{cm}^2$ show an increase in the absorption coefficient $\alpha$ which, for photon energies $0.1<E<1.0$ eV, is expressed by $\Delta\alpha=A\exp(B\times E^2)$, where $A$ and $B$ are constants.[1] At fast-neutron fluences greater than $6\times10^{16}$ $n/\mathrm{cm}^2$ the absorption coefficient varies as the square of the photon energy.[1-4] McNichols, Hayes, and Ginell[5] have shown that this energy-squared dependence of the absorption coefficient can be explained by small metallic disordered regions in an otherwise normal host semiconductor lattice. Their theory predicts an absorption peak resulting from electromagnetic excitations of electron plasma oscillations within these regions. The energetic position of the plasma resonance maximum as well as the shape of the absorption band depend on the optical constants of the host lattice. In this work the metallic plasma resonance was studied by using an optical modulation technique. The measurements were carried out in the photon energy range from 1.27 to 3.35 eV, where the transitions $E_0$, $E_0+\Delta_0$, $E_1$, and $E_1+\Delta_1$ occur.

Assuming a narrow distribution of metallic zone sizes, the absorption coefficient near the band edge is given by[5]

$$\alpha(E)\approx\alpha_0(E)+\frac{9\epsilon_0 nfE_0{}^4E^2}{\sigma_0 c\hbar^2}\,\frac{\epsilon_r-\epsilon_i[(\epsilon_0 E/\hbar\sigma_0)(1+\Gamma^{-2}E^2\tau^2)-\hbar^{-1}E\tau]}{(E_0{}^2-E^2)^2+\hbar^2\Gamma^2E^2}, \tag{1}$$

where $E_0{}^2\approx\hbar^2\sigma_0/\epsilon_0\tau(1+2\epsilon_r)$ and $\Gamma^2\approx1/\tau^2$ [$\alpha_0(E)$ being the absorption coefficient of the host medium]. $\epsilon_0$ is the dielectric constant of vacuum, $n$ the refractive index of the host semiconductor material, and $f$ the volume fraction occupied by metallic regions. The quantities $\epsilon_r$ and $\epsilon_i$ are the real and imaginary parts of the relative dielectric constant of the host lattice. $\sigma_0$ is the conductivity of the metallic particles and $\tau$ is the electron relaxation time in the metallic particles.

According to Eq. (1) a periodic change of the absorption coefficient, $\alpha(E)-\alpha_0(E)$, due to metallic regions is produced when the dielectric constant of the host lattice is modulated. In this work the modulation was done by modulating the reflectivity of the host lattice with the electrolytic electroreflectance (ER) technique.[6] Thus an

additional modulation of the reflectivity (corresponding to the modulation of $\alpha - \alpha_0$) in the irradiated samples should occur.

The GaAs samples used were high-resistivity $n$-type single crystals with a carrier concentration of about $10^{13}$ cm$^{-3}$. The irradiation at 300–310 K was done in the core of the Triga Mark II reactor in Otaniemi. The samples showed higher resistivity after the irradiation periods, which possibly means that the light penetration depth and accordingly the surface field conditions were somewhat affected by the irradiation. On the other hand by using high-resistivity samples, possible difficulties with impurity-associated ER peaks[6,7] were avoided. During the ER measurements the dc bias and the square-wave ac modulating voltage were kept at $-1$ and 1 V, respectively.

For fluences up to $3.3\times10^{17}$ $n/\mathrm{cm}^2$ (neutron energy > 10 keV) the ER spectrum near the $E_0$ gap shifted nonlinearly toward lower energies, the total shift saturating to a value of 30 MeV. The shape of the spectrum remained unchanged except for a small broadening of the low-energy side of the $E_0$ peak below 1.36 eV. The shift toward lower energies corresponds to the exponential dependence of $\alpha$ discussed earlier, the behavior being attributed to a presence of a band tail.[1] The broadening corresponds to beginning plasma absorption.

In Fig. 1 the curves $a$ and $b$ are the measured ER spectra for fluences $>6\times10^{16}$ $n/\mathrm{cm}^2$ (neutron energy > 10 keV). An appearance of a new peak with increasing fast-neutron fluence is seen at 1.33 eV. The curves $d$ and $e$ are the calculated curves. They were obtained from the measured ER spectrum of unirradiated GaAs by first shifting it 30 meV toward lower energies (curve $c$ in Fig. 1). The $\Delta\epsilon_r$ and $\Delta\epsilon_i$ curves were calculated from this $\Delta R/R$ spectrum using the method described in Ref. 6. The values of the refractive index were taken from an article by Philipp and Ehrenreich.[8] The change in the absorption coefficient, $\Delta(\alpha - \alpha_0)$, was obtained from Eq. (1). Applying the Kramers-Kronig analysis, the relative change in reflectivity $(\Delta R/R)_\alpha$ due to $\Delta(\alpha - \alpha_0)$ was calculated and added to the original $\Delta R/R$ (curve $c$ in Fig. 1). Numerical calculations were carried out on an HP 2000 computer. A satisfactory agreement with the experimental curves is achieved with $E_0 = 1.33$ eV and $\tau = 3\times10^{-14}$ sec. According to these values the volume fraction $f = 1.5\times10^{-4}$ is occupied by metallic disordered regions at $3.3\times10^{17}$ $n/\mathrm{cm}^2$. This $f$ value is smaller than that obtained from the absorption measurements below the edge.[1] The discrepancy may largely be removed by a better choice of the starting curve $\Delta R/R$, which could be narrower at high fluences because of the irradiation-induced decrease in carrier concentration. At $3.3\times10^{17}$ $n/\mathrm{cm}^2$ a narrowing can be seen on the positive high-energy swing of the $E_0$ peak which should not, according to the calculations, markedly be affected by the metallic plasma resonance absorption.

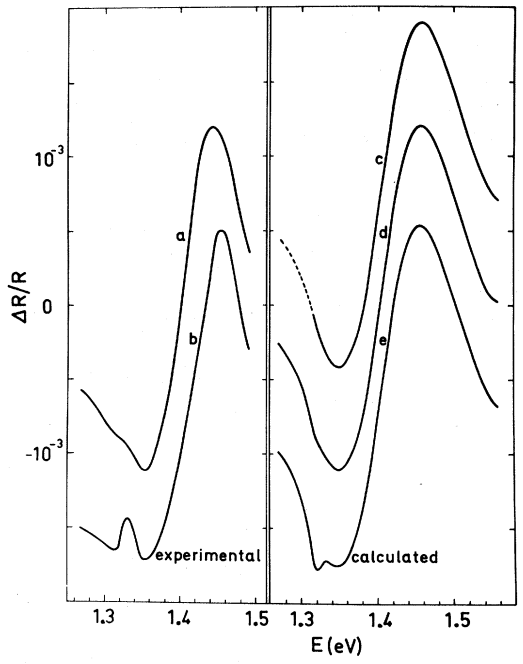


FIG. 1. Curve $a$, the measured electroreflectance spectra of GaAs at 300 K after a fast-neutron fluence of $7.3\times10^{16}$ $n/\mathrm{cm}^2$; and curve $b$, after a fast-nuetron fluence of $3.3\times10^{17}$ $n/\mathrm{cm}^2$ (neutron energy > 10 keV). The irradiation temperature was 300 to 310 K. Curves $d$ and $e$ were calculated from curve $c$. The volume fraction occupied by small metallic regions, $f$, is 0, $3.3\times10^{-5}$, and $1.5\times10^{-4}$ for curves $c$, $d$, and $e$, respectively. $E_0 = 1.33$ eV and $\tau = 3\times10^{-14}$ sec in Eq. (1). $\Delta R/R$ refers to curves $a$ and $d$, while the others have been shifted vertically.

The measurements suggest for the plasma resonance an energy value of $E_0 = 1.33$ eV. From this value an average number $\approx 0.5$ conduction electron per metallic atom can be evaluated.[5] The conductivity of metallic particles[9] $\sigma_0 = n_e e^2\tau/m$ can thus be calculated ($n_e$ is the number of conduction electrons of charge $e$ and effective mass $m$ per unit volume). A value $\sigma_0 = 3\times10^7\ \Omega^{-1}\ \mathrm{m}^{-1}$ is obtained. This is close to the conductivity of the metallic form to which the semiconducting

GaAs can be converted by application of ultrahigh pressure.[10] The use of the modulation spectroscopy should be fruitful also in the study of radiation damage in other compounds like CdTe and CdS,[2] where an energy-squared dependence of $\alpha - \alpha_0$ has been observed.

*Present address: Helsingin kaupungin sähkölaitos (Helsinki Electricity Works).

[1]K. V. Vaidyanathan, L. A. K. Watt, and M. L. Swanson, Phys. Status Solidi (a) 10, 127 (1972).

[2]L. W. Aukerman, P. W. Davis, R. D. Graft, and T. S. Shilliday, J. Appl. Phys. 34, 3590 (1963).

[3]L. K. Vodop'yanov and N. I. Kurdiani, Fiz. Tverd. Tela 8, 254 (1966) [Sov. Phys. Solid State 8, 204 (1966)].

[4]T. Pankey and J. E. Davis, J. Appl. Phys. 41, 697 (1970).

[5]J. L. McNichols, P. Hayes, and W. S. Ginell, IEEE Trans. Nucl. Sci. 14, No. 6, 46 (1967).

[6]M. Cardona, K. L. Shaklee, and F. H. Pollak, Phys. Rev. 154, 696 (1967).

[7]E. W. Williams and V. Rehn, Phys. Rev. 172, 798 (1968).

[8]H. R. Philipp and H. Ehrenreich, Phys. Rev. 129, 1550 (1963).

[9]N. F. Mott and H. Jones, *The Theory of the Properties of Metals and Alloys* (Dover, New York, 1958), pp. 111, 268.

[10]S. Minomura and H. G. Drickamer, Phys. Chem. Solids 23, 457 (1962).

# Elastic Constants of Argon and Neon by Brillouin Scattering from Single Crystals near Their Triple Points*

S. Gewurtz,† H. Kiefte,‡ D. Landheer,§ R. A. McLaren,† and B. P. Stoicheff,
*Department of Physics, University of Toronto, Toronto 181, Canada*
(Received 24 August 1972)

The adiabatic elastic constants of single crystals of neon at 24.3 K and of argon at 82.0 K have been determined by Brillouin scattering. For argon the values are $C_{11}=2.33\pm0.08$, $C_{12}=1.49\pm0.06$, $C_{44}=1.17\pm0.07$, in units $10^{10}$ dyne/cm$^2$, with the elastic anisotropy $A=2.80\pm0.60$; for neon, the values are $C_{11}=1.175\pm0.020$, $C_{12}=0.740\pm0.020$, $C_{44}=0.595\pm0.015$, and $A=2.74\pm0.25$.

The elastic constants of the rare-gas solids, and their dependence on temperature, provide sensitive tests of recent theories of lattice dynamics.[1-3] Especially important are values of the constants at high temperatures in order to check the anharmonicities of assumed interatomic potentials[4,5] and the possible relevance of many-body forces.[6] Neon, because of its small atomic mass and consequent large-amplitude lattice vibrations, requires more detailed calculations at high temperatures, and therefore should provide a very stringent test of theory. However, only one determination of its elastic constants has been reported to date,[7] based on neutron scattering measurements for a crystal at 4.7 K and for a second crystal under pressure at 4.7 and 25 K. Argon is the most throughly studied of the rare-gas solids both experimentally and theoretically. In spite of this activity with argon, significant difficulties remain with our present knowledge of its elastic constants.[8-13] The experimental values do not show good agreement among themselves nor is there satisfactory agreement between experimental and theoretical values.[1,2]

We report here on the determination of the adiabatic elastic constants of neon and argon near their triple points, based on Brillouin scattering experiments with single crystals. The experimental techniques were essentially the same as those described by Gornall and Stoicheff[14] in their determination of the elastic constants of Xe single crystals. Crystal samples were grown from the liquid in equilibrium with the vapor, in cylindrical cells (~2 mm i.d. and 10 mm long) mounted with their axes vertically in the tail sections of suitable Dewars. Laue x-ray transmission photographs were used to check that the samples were single crystals, and to establish (within ~30′) their orientation as specified by the Euler angles $\theta, \varphi, \chi$ (with $\varphi$ corresponding to rotation about the vertical axis). Eight single crystals of Ne grown at 24.3 K and one single crystal of Ar at 82.0 K were used in the present study.

For the experiments with solid argon, radiation from a stabilized, single-frequency, He-Ne laser, operating at 6328 Å with 6 mW output, was directed along the vertical axis of the cell