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FAR-INFRARED ABSORPTION OF LARGE ELECTRON-HOLE DROPS IN STRESSED Ge*

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LONG TITLE

The far-infrared attenuation spectrum due to a large electron-hole drop in inhomogeneously stressed Ge has been measured and compared to the attenuation by small drops in unstressed Ge. The spectrum is analyzed using the full Mie theory for the absorption due to a large sphere; the experimental results are interpreted as bulk plasma absorption in a drop with pair density considerably lowered by the strain.

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AUSZUG

Das Attenuations-Spektrum eines grossen Elektron-Lock Tröpfchens in inhomogen beanspruchtem Ge wurde im fernen Infrarot ausgemessen und mit demjenigen kleiner Tröpfchen in spannungsfreiem Ge verglichen. Das Spektrum wurde mit Hilfe der vollständigen Mie-Theorie für Absorption in grossen Kugeln ausgewertet. Die experimentellen Resultate werden zurückgeführt auf Plasma Absorption in einem Tröpchen mit - infolge der Spannung - beträchtlich verminderter Paardichte.

It has been determined[1-4] that a roughly spherical mass of electron-hole liquid (hereafter termed a γ-drop) can be formed in a potential well in non-uniformly stressed crystals of optically pumped pure Ge. Such drops can have radii as large as 300 μm and lifetimes as long as 500 μs compared with radii of typically 5 μm and lifetimes of about 40 μs for the small droplets (α-drops) which exist in unstrained crystals. This enhanced lifetime is due to a lowering of the electron-hole density in the γ-drop liquid[5] relative to the value of $n = 2 \times 10^{17}$ cm^{-3} for α-drops. A γ-drop density of $n \sim 7 \times 10^{16}$ cm^{-3} may be directly inferred from the reduced linewidth of the luminescence spectrum.[2]

We have measured the far-infrared attenuation of both γ- and α-drops over the frequency range from 25 cm^{-1} to 200 cm^{-1}. At a given excitation level, the γ-drop attenuation is nearly an order of magnitude larger than that due to α-drops. Despite the lower γ-drop density, the attenuation spectrum is similar to the unstrained case[6,7]: both show a broad maximum in attenuation at about 70 cm^{-1}. We present a theoretical analysis based on the exact Mie theory of scattering by a large sphere which shows that the observed γ-drop spectrum is consistent with a lowered pair density.

Samples of ultra-pure germanium ($N_A + N_D \simeq 10^{11}$ cm^{-3}) cut into circular discs 4 mm in diameter and 1.4 mm thick were mounted in a ring-shaped Kel-F plastic holder. The normal to the plane of the disc was a ⟨001⟩ crystal axis. Strain was applied perpendicular to this axis by means of a nylon screw as described in references 3 and 4. The position of the drop in the potential well arising from the inhomogeneous strain field which is produced by this means is described in reference 4. Two strain configurations

were studied, corresponding to the nylon screw axis T parallel to the ⟨100⟩ and the ⟨110⟩ crystal axes. Attenuation measurements were also made on an unstrained sample to allow a comparison between the spectra of α- and γ-drops.

The existence of a single γ-drop in the ⟨110⟩ sample and two γ-drops in the ⟨100⟩ sample was confirmed both before and after performing the far-infrared attenuation experiments by using a vidicon camera[3] to monitor the near-infrared recombination radiation at ~709 meV. From these photographs, the radii of the γ-drops were estimated. These large drops were originally discovered by the observation of Alfvén wave resonances in samples with T || ⟨110⟩.[1,2] We have now observed Alfvén resonances in our T || ⟨100⟩ sample, at magnetic fields higher than 10 kG; these resonant fields are consistent with the drop radii measured by imaging. The decay lifetimes τ of the drops were also measured: for T || ⟨110⟩ τ was 500 μs and was independent of temperature between 1.8 and 4.2 K; for T || ⟨100⟩ τ was 380 μs at 1.8 K but decreased at higher temperatures, possibly because of evaporation of electron-hole pairs from the relatively shallow potential well in this strain configuration. In neither of the strained samples was there any evidence of a short decay lifetime ($\tau \simeq 40$ μs) which is characteristic of small α-droplets in unstressed Ge.

The samples were immersed directly in liquid helium which could be cooled to 1.5 K. A light pipe of aluminized mylar transmitted both the far-infrared radiation from a Fourier transform spectrometer and the pumping radiation from a tungsten-halogen lamp to the front circular face of the sample. A short light pipe adjacent to the back face of the sample carried the transmitted radiation to a germanium bolometer at 1.2 K.

In this geometry the large aperture detector collects a significant fraction of the radiation which is scattered from the drop so that the attenuation measurement is more closely related to the absorption than to the extinction.

Figure 1 shows the absorption spectra of γ-drops in the two strained samples for a range of optical pumping levels. The spectra are plotted as $\ln(I_D/I_L)$ where I_L and I_D are the transmitted far-infrared intensities with and without optical pumping. For each of the curves the values of $\ln(I_D/I_L)$ have been normalized to give the same peak absorption. The optical pumping levels and the maximum values of $\ln(I_D/I_L)$ are given in the figure caption. As a comparison, the figure also shows an absorption spectrum obtained for α-drops in an unstrained sample, which closely resembles that previously obtained by other workers.[6,7] Inspection of the spectra shows that the ⟨110⟩ γ-drop absorbs relatively more strongly than the ⟨100⟩ γ-drops and the α-drops on the low frequency side of the maximum. The ⟨100⟩ γ-drop and the α-drops have an almost identical line-shape. The most striking difference between the absorption spectra for the two types of drop is that at a given level of optical pumping, the γ-drop absorption is about one order of magnitude larger than that for α-drops. This enhanced absorption is the result of the longer lifetime of carriers in the γ-drops, so that at a given pumping level the total equilibrium number of carriers is an order of magnitude higher for our strained crystals.

Despite the similarity in lineshapes, theoretical analysis of these data shows that the electron-hole density in the γ-drops is considerably lower than that obtained for α-drops. We have calculated the absorption due to a sphere of radius a, using exact results of Mie theory[8] and

assuming a dielectric constant

$$\frac{\varepsilon}{\varepsilon_L} = 1 - \frac{\omega_p^2}{\omega(\omega + i/\tau)} \tag{1}$$

where $\omega_p^2 = 4\pi ne^2/\varepsilon_L m_{opt}$ is the plasma frequency inside the drop, m_{opt} is the combined optical effective mass of the conduction and valence bands: $m_{opt}^{-1} = m_{oe}^{-1} + m_{oh}^{-1}$; n is the plasma density; ε_L is the lattice dielectric constant; and τ is the plasma momentum relaxation time.

The α-drop spectrum has previously been analyzed[6] using the small sphere (dipole) approximation[8] to Mie scattering theory which predicts a peak in absorption at a frequency of $\omega_p/\sqrt{3}$. This approximation is only valid, however, where $q = 2\pi a/\lambda << 1$, where λ is the wavelength in germanium. For the large γ-drops $q >> 1$, and we have analyzed the absorption using the exact Mie expression for multipole absorption, retaining all terms up to the 2^{ℓ}-pole, where ℓ is an integer greater than q. The calculated absorption spectrum for a large drop (Fig. 2) has a broad resonance with a peak which is shifted to a frequency slightly higher (10-20%) than ω_p, the amount of shift increasing with drop radius.

Thus since the α and γ absorption peaks are observed to occur at essentially the same frequency, the α-drop density must be larger than three times the γ-drop density. Figure 2 shows that the above theory gives a reasonable fit to the γ-drop absorption for T $||$ ⟨100⟩; however, it cannot explain the enhanced absorption on the low frequency side of the T $||$⟨110⟩ spectrum. For both γ-drop spectra, we find a theoretical $\omega_p = 6.5 \pm 1.3$ meV. The uncertainty is due to the range of values of $\omega_p\tau$

that can be fitted.

The above interpretation ignores the contribution of intervalence band transitions to the dielectric constant.[9-13] These transitions have been found to considerably alter the lineshape of the resonance without significantly changing the frequency of the peak[11-13]. A similar calculation for γ-drops is complicated by the inhomogeneous strain, but this strain also weakens the intensity of the interband transitions.[14]

A determination of the plasma density n from ω_p is complicated because the optical effective mass is stress dependent. It varies from 0.081 m_o at zero stress to 0.046 m_o at high stress where the two valence bands are completely decoupled. From the frequency shift of the luminescence line[18] relative to that for an unstrained crystal, the maximum value of the stress at the γ-drop is estimated to be 5kg/mm^2 which is not sufficient to completely decouple the bands. Consequently, using the lower and upper limits of the optical mass and assuming ω_p = 6.5 meV, the γ-drop plasma density is estimated to be between 2.2 and 3.8 × 10^{16} cm^{-3}. Because of the many assumptions involved in deriving this value, we consider it to be in reasonable agreement with previous estimates of the γ-drop density[2], but it is considerably reduced from the α-drop value.

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optical mass. In zero stress, $m_{oh} = 0.25\ m_o$[16]; in the high stress limit $m_{oh} = 0.075\ m_o$ for all of T || ⟨100⟩, ⟨110⟩, ⟨111⟩, when the hole bands are decoupled into ellipsoidal energy surfaces.[17]

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Figure Captions

Figure 1 The absorption spectra of electron-hole drops in three samples of Ge plotted as $\ln(I_D/I_L)$. The values of $\ln(I_D/I_L)$ in each curve are normalized so that they are the same height at the peak. The following are the directions of the applied inhomogeneous strain, the incident optical pumping level P and the peak values α_m of $\ln(I_D/I_L)$ before normalizing:

(i) ● - T || ⟨110⟩, P = 70 mW, α_m = 0.47

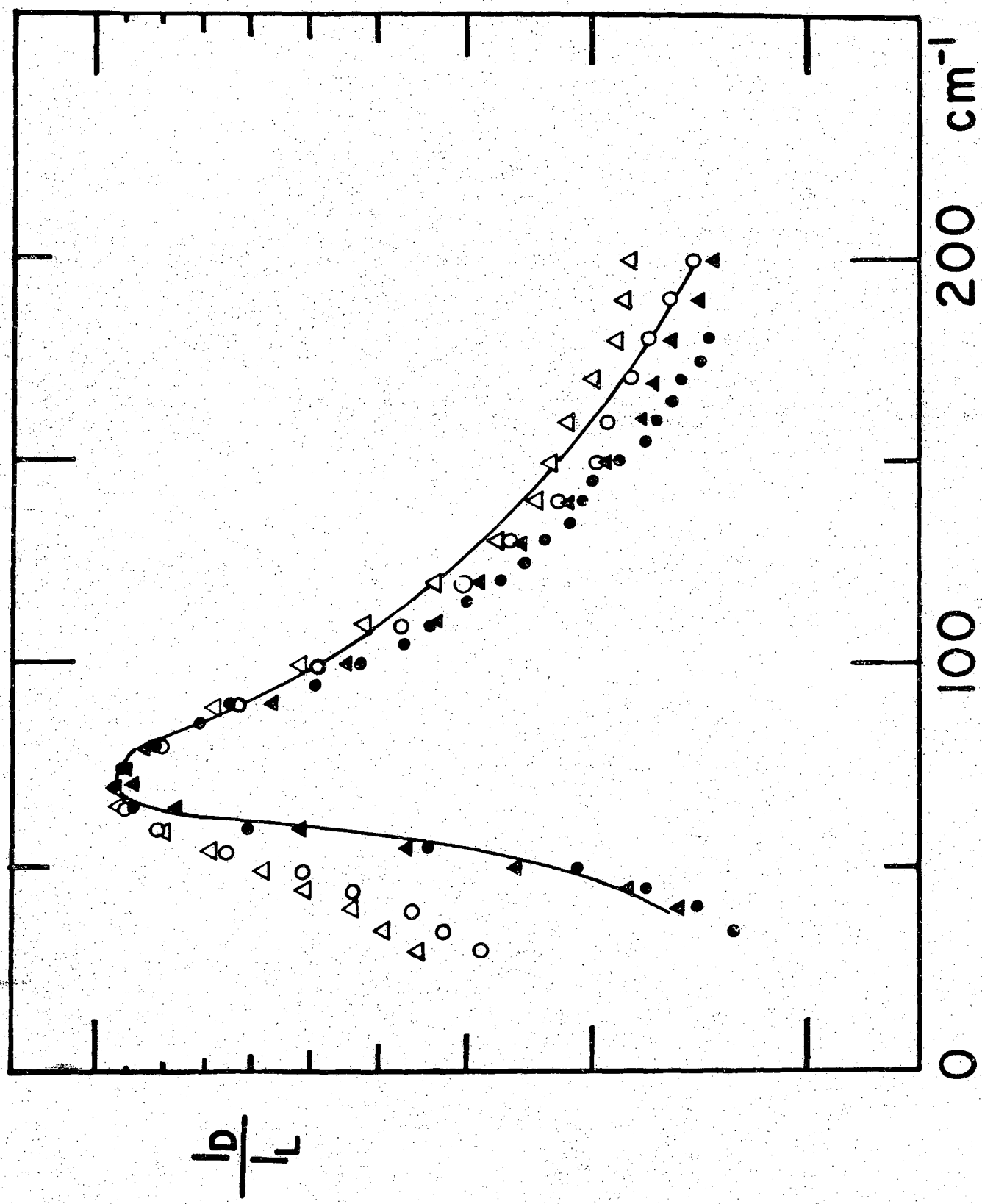
(ii) ▲ - T || ⟨110⟩, P = 7 mW, α_m = 0.19

(iii) ▲ - T || ⟨100⟩, P = 70 mW, α_m = 0.26

(iv) ● - T || ⟨100⟩, P = 11 mW, α_m = 0.12

(v) Continuous curve: α-drops in unstrained crystal, P = 70 mW, α_m = 0.06

Figure 2 Solid line: theoretical Mie absorption of an electron-hole drop calculated for ω_p = 6.8 meV, Radius a = 250 μm, $\omega_p\tau$ = 100. ● - experimental data (iv) of Figure 1 [T || ⟨100⟩].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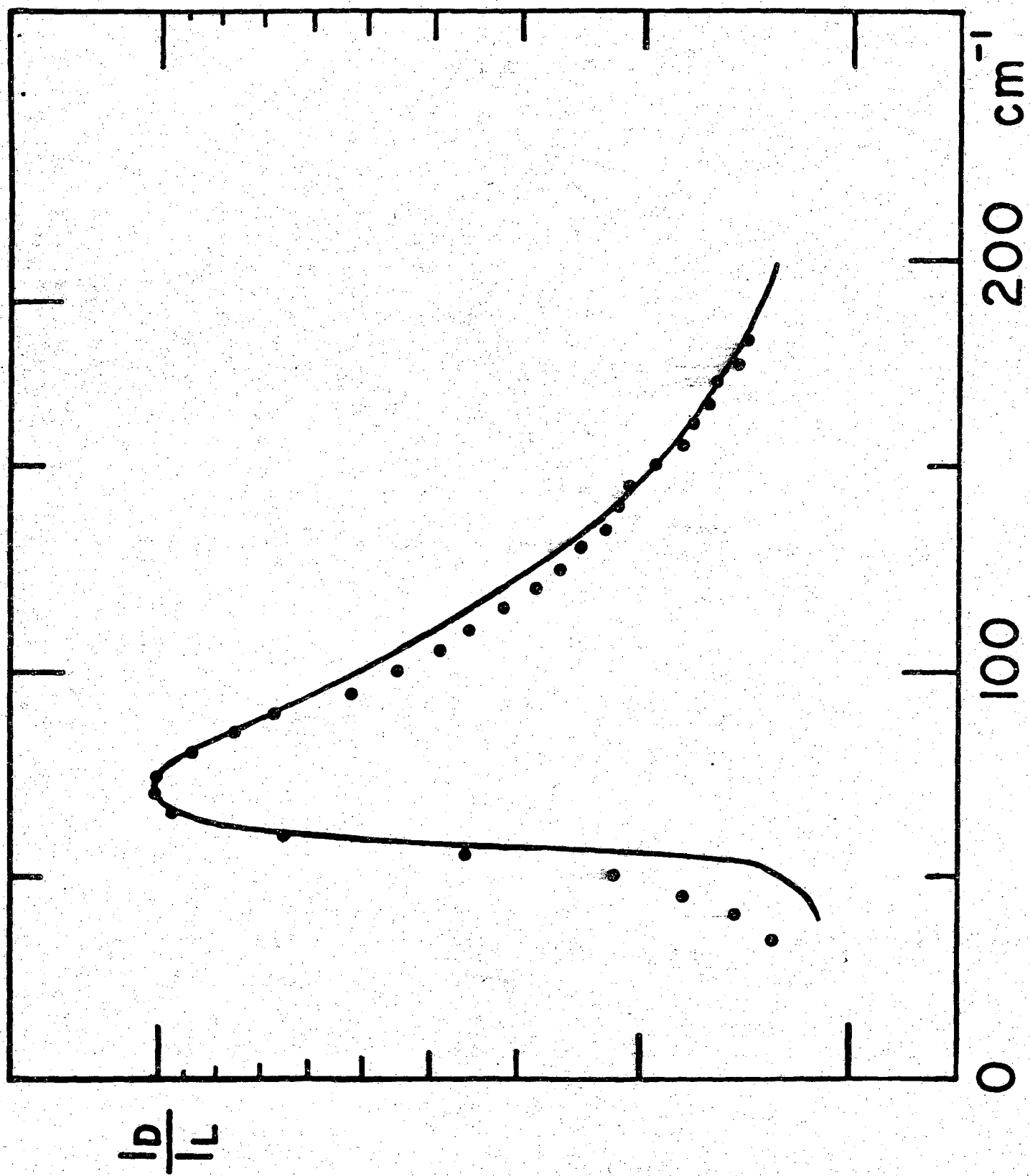

Fig.

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