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Publication Date
1977-04-01

Submitted to Physica Status Solidi(b)

LBL-6049
Preprint

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ABSTRACT

We have measured by infrared imaging the shape of a strain-confined electron-hole drop in germanium in an applied magnetic field, $H \leq 22$ kOe. A considerable distortion from sphericity is observed for all field orientations and stress geometries studied. We find that in most cases the drop flattens along the field direction. For $H \,||\, \langle 111 \rangle \,||$ (applied stress) the drop shape depends markedly on the position of the light excitation spot on the crystal. The dimension parallel to the field decays more rapidly than the perpendicular dimension. Our data strongly support a dynamic interpretation in which the recombination currents of electrons and holes give rise to the field-induced distortion.

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Die Form eines durch mechanische Spannung lokalisierten Elektron-Loch Tropfens in Germanium wurde mit Hilfe von Ultrarot Abbildung bei Magnetfeldern, H $\lesssim$ 22 kOe, bestimmt. Erhebliche Abweidungen von der Kugelform wurden für alle untersuchten Magnetfeldorientierungen und Spannungsgeometrien beobachtet. In den meisten Fällen fleicht sich der Tropfen in Richtung Magnetfeld ab. Für H || ⟨111⟩ || Spannung hängt die Tropfenform stark von Ort des Einfalls des Anregungslichts ab. Die Tropfengrösse parallel zum Feld nimmt schneller ab als die senkrecht zum Feld Stehende. Unsere Mendaten konnen best mit einem dynamischen Model indem die Rekombinationsflüsse der Electronen und Löcher Anlass zu magnetfeldinduzierter Verformung geben erklärt werden.

The application of a contact stress to the surface of a Ge crystal can produce several distinct potential energy minima for electron-hole drops (EHD) [1-3]. The potential minima are in regions of large octahedral shear strain [4] and are located along the ⟨111⟩ directions in the crystal. For a contact stress applied parallel to a ⟨111⟩-crystal direction, only a single minimum is produced.

Large single EHD (termed γ-drops) are formed at each potential minimum [1-3, 5-7] through the aggregation of smaller drops, excitons, and carriers, which are all attracted toward the minimum. Fig. 1a is the luminescence image of one such drop, detected by focusing its recombination luminescence at 1.75 μm onto an infrared-sensitive image tube. In this experiment the sample is optically excited by a focused Argon ion laser beam (5145Å); the absorbed power is $P_{abs} \approx 35$ mW. In the absence of a magnetic field, the shape of the strain-confined liquid is determined by the equipotential surfaces of the strain well, as shown in Fig. 1b. This is a numerical computer calculation for the experimental stress geometry taking into consideration the anisotropic band structure of Ge.

In an applied magnetic field a large distortion in the shape of the strain-confined drop occurs, as observed independently by Störmer and Bimberg [8,9] (SB) and by us [10]. In an attempt to detect a new phase transition of the liquid, SB observed the drops in fields up to 190 kOe and concluded that the suggested [11] van der Waals lattice of e-h cylinders does not form even at these high fields. The principal distortion in drop shape, we have found, occurs in fields below 20 kOe, and is due to a completely different phenomenon. SB have attempted to explain the observed distortion solely by the static bandshifting caused by the field H. In this paper we conclude both from calculation and experiment that the observed shape change arises primarily from the dynamic nature of the electron-hole droplet system.

In an applied magnetic field the energies of the 4 conduction band valleys can shift with respect to each other because the cyclotron masses will in general be different for each valley. In principle this could modify the shape of the potential well [8] by changing the relative population of the valleys. In the experimental conditions $H \perp \langle 111 \rangle$, this shape change could occur only if more than one conduction band is occupied by electrons inside the γ-drop. This is because for $H \perp \langle 111 \rangle$, a magnetic field further raises the three unoccupied valleys in energy with respect to the occupied valley. EHD are attracted by an octahedral strain maximum only if the strain is large enough so that just one conduction band valley is occupied [3,12]. For example, in Fig. 1b the shaded regions are the only parts of the crystal where more than one valley is occupied. Hence, until the γ-drop is large enough to fill the unshaded region in zero field, a magnetic field applied perpendicular to the stress direction would have no effect on the shape of the drop, contrary to experiment. In Fig. 2 the EHD energy contours are recalculated as in Fig. 1b, but now with a 50 kOe magnetic field applied parallel to the $\langle 11\bar{2} \rangle$-direction. As expected, the shape of the constant energy contours is affected only in the region of the crystal shaded in Fig. 1b. Thus the static bandshifting mechanism cannot explain the experimental results reported here, where a large distortion is observed even for $H < 20$ kOe [13].

Our experimental results are shown in Fig. 3. In these experiments the 4 mm × 4 mm × 2 mm high-purity dislocation-free Ge sample is placed on a quartz plate and variably stressed by a nylon plunger attached to a calibrated spring arrangement. The sample is immersed in superfluid He^4, at T = 1.7 K. A mirror allows viewing along the stress direction, ⟨111⟩. Figs. 3c and d show that in a field of 20 kOe the drop flattens along the applied field direction. Figure 4 shows the magnetic field dependence of the distortion. These data were obtained by translating the image of the EHD across a narrow slit and measuring the transmitted luminescence intensity. In this way a spatial profile of the drop luminescence parallel and perpendicular to the magnetic field direction was obtained, giving the radial extent of the droplet in these two directions. The data here are taken for relatively high light level, $P_{abs} \approx 90$ mW, and moderate applied force, 9 kg. This force is applied across a contact area ~ 1 mm^2 as in [3]. The principal results are that (a) the primary change in shape occurs for $H \lesssim 10$ kOe and that (b) above $H \approx 10$ kOe the amount of distortion appears to saturate with increasing field. The field at which saturation occurs depends on the magnitude of the applied stress and on the drop size. (See Figs. 5 and 7.)

The effect of changing the applied stress is displayed in Fig. 5. In a given magnetic field the distortion for 4.5 kg force is considerably greater than for 18 kg. Not surprisingly, the effect of the magnetic field on drop shape is less for a deep potential well than for a shallow one, since the strain gradient acts as a restoring force. For the samples reported on here the luminescence decay time is measured to be ≈ 500 μs. Fig. 6 shows that about 20% variation in this lifetime is observed for applied fields up to 25 kOe.

SB suggest [9] that, even though only one conduction band minimum is occupied at the center of the strain well, it is possible that near the surface of the drop the strain is sufficiently reduced that several minima are occupied. While the calculation of Figs. 1b and 2 indicate that this is unlikely, it is possible to give more direct experimental evidence. If multiple valleys are occupied only near the surface of a γ-drop, then the flattening effect should be much less pronounced for a smaller drop, and should vanish for drops of radius $R < R_{min}$, for which all electrons are in a single conduction band at H = 0. Assuming for the moment that the distortion were due to static bandshifting, a reasonable estimate for R_{min} should be the saturated value of $R_{\parallel}$ at high fields, which for the data of Fig. 4 would yield $R_{min} \simeq 300$ μ. Fig. 7 shows that this is not the case. For the same sample and stress condition as in Fig. 4, the laser pump intensity was reduced until the initial drop radius was ≈ 150 μ. Clearly, the magnitude of the flattening has not been significantly reduced.

A direct experiment for determining the influence of static bandshifting on the shape of the EHD is to apply the magnetic field along a ⟨001⟩-crystal axis. For this field direction all four conduction bands are shifted equally with H; hence, no change in the shape of the potential well can occur. The experimental result is reproduced in Fig. 8. Again the applied stress is along ⟨111⟩ as above, but here the field is directed along ⟨001⟩. The flattening is evident in Fig. 8c. We note that SB do not observe a distortion of this magnitude in a disc of Ge with H || ⟨ 001 ⟩. However, the amount of distortion is critically dependent upon a number of parameters: the magnitude of the applied stress, the lifetime of the drop, and the distribution of the flow of carriers into the surface of the drop. A difference in any of these parameters may explain the apparent discrepancy. The observation of a flattening for H || ⟨ 001 ⟩ proves conclusively that the field-induced distortion cannot be explained solely by a static bandshifting mechanism.

We propose a dynamic model which qualitatively explains the present observations. Because of the continuous recombination of electrons and holes inside an EHD, a drop can remain in steady state only if there is a net particle flow inward from its surface. This recombination current $\vec{\Gamma} = n_o\vec{v}$, whose existence was noted by Kaminskii and Pokrovskii [14], is governed by the continuity equation:

$$\vec{\nabla}\cdot\vec{\Gamma} = -n_o/\tau_o \quad (1)$$

where n_o is the pair density and τ_o the pair recombination time. The current is supplied by photoproduced droplets, excitons and carriers which are created at the crystal surface and flow in the strain gradient to the surface of the large drop. The particle flow pattern within the drop will depend on the spatial distribution of carriers absorbed at the drop surface [15]. For a spherically symmetric flow into the surface, the recombination currents in zero field are shown in Fig. 9a. For this case Eq. (1) yields for the drift velocity $\vec{v} = -\vec{r}/3\tau_o$. For a carrier near the surface of a drop with radius R = 200 μ and lifetime τ_o = 500 μsec, the drift velocity is approximately 15 cm/sec.

In a magnetic field the recombination currents are deflected by the Lorentz force, as shown in Fig. 9b. Since electrons and holes are deflected in opposite directions, there will be a net azimuthal electrical current about the field direction. This current gives rise to a net paramagnetic (i.e. positive) magnetization M_R, the 'recombination magnetism' [14]. For a spherical droplet, the contribution to the magnetization by either electrons or holes is given by $M_R = 4\pi n_o e\omega_c \tau R^5/45c\tau_o$, with τ the carrier scattering time and $\omega_c = eH/m^*c$ the cyclotron frequency.

The distribution of recombination currents and hence the magnetization depends upon the shape of the drop. The total energy of the drop can be lowered if the drop distorts in such a manner as to increase M_R, since the magnetic energy is $E_m = -\frac{1}{2} M_R \cdot H$. The potential energy of e-h pairs in the strain well $E_s(r)$ acts as a restoring force; thus, the minimization of the total energy $E_m + E_s$ determines the drop shape in a magnetic field. In general, the recombination magnetism is increased by increasing the radial currents perpendicular to the field. This corresponds to a flattening of the drop along the field direction, as is generally observed experimentally.

As a consequence of this dynamic mechanism, we expect the drop flattening can be varied by moving the focused laser spot on the crystal surface, since the recombination current flow pattern depends on the carrier flux distribution at the drop surface. For example, if all the carriers enter the drop through a small area of surface lying on the drop diameter parallel to the magnetic field (Fig. 9c and d), then the recombination current perpendicular to H will be predominantly outward, from the center of the drop toward the surface. In this case the resultant recombination magnetism is diamagnetic, and the drop should elongate along the magnetic field, reducing the recombination currents perpendicular to H.

We have in fact observed a change in shape with a change in pump geometry by aligning the field parallel to the applied stress, H || ⟨111⟩, and translating the excitation spot across the crystal surface. Fig. 10 shows how the drop shape changed as the laser spot was translated downward, away from the contact point. The top photo corresponds to the excitation spot very near the stressed surface. In the bottom photo the light excitation is 1.5 mm from the top of the crystal, well below the observed drop position. When the excitation is well away from the stressed surface, the boundary conditions are apparently similar to the case of Fig. 9c and d. This data clearly shows the dynamic nature of the drop distortion, which depends upon the exact geometry of the particle currents. It should be noted that no shape change due to excitation position has been observed in zero magnetic field.

At high fields, the carriers are confined in cyclotron orbits, and any motion perpendicular to the field is inhibited. Of course, since the drop remains stable there must still be a recombination current. As carriers decay, a density gradient is created in the drop. This gradient produces a pressure which acts to move carriers perpendicular to the field. We suspect that it is partly this transverse 'magnetoresistance' which causes the flattening to saturate at high fields [16].

The decay of γ-drops is strongly influenced by the fact that charged carriers flow much more easily parallel to the field than perpendicular to it. Fig. 11 shows the variation of the drop radius as the γ-drop decays. The data are obtained by a time-resolved imaging technique [17]: We use basically the same slit-scanning procedure as in Figs. 4, 5 and 7; however, by means of gated boxcar integration the luminescence profile is measured at discrete times after the excitation light is switched off. Within a few microseconds after the laser pulse, nearly all of the non-equilibrium carriers are contained within the drop [18], and no net particle flow into the drop remains. Hence the spatial decay of the isolated strain-confined liquid in a magnetic field is determined. The experiment was performed for the stress and field geometry of Fig. 10, for the excitation conditions of both Fig. 10a and 10d. The data in Fig. 11 show that the dimension of the drop parallel to the magnetic field decays more rapidly than the dimension perpendicular to the field; and this is true independent of the initial drop shape before the light is removed [19]. It is clear that the shape of the electron-hole drop depends upon the dynamic particle currents within the drop which are altered by the magnetic field.

In conclusion we note that the recombination magnetism may be either paramagnetic or diamagnetic depending upon the boundary conditions of the drop (i.e. surface flux). The ordinary Landau diamagnetism is a volume effect which to first order should not depend on drop shape, and therefore it has been neglected in the above discussion. An exact calculation of the recombination magnetism requires the solution of a complicated magnetohydrodynamic boundary value problem. A detailed study of this will be published shortly [16], but it is already apparent that the experimental evidence presented here supports such a dynamical explanation of the magnetostriction.

We would like to thank W. L. Hansen and E. E. Haller for supplying us with the ultrapure Ge samples, and for the use of the infrared vidicon. Also, we thank H. L. Störmer and D. Bimberg for sending us their results prior to publication.

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[13] If there are two spatially separate drops in the crystal, the electrons will occupy a different ⟨111⟩-valley in each [3]. Consequently a magnetic field can alter the relative populations of carriers in the two drops as observed in [9].

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[15] We assume to a first approximation that most of the photoexcited carriers at the crystal surface are rapidly bound into excitons and droplets. A more detailed model would also have to include modifications of particle currents outside the drop, which we neglect here. Preliminary experiments on our samples excited by a focused laser show that the shape of the cloud of small drops in unstressed Ge is not significantly modified by a magnetic field $H \leq 20$ kOe at 1.8 K. The time resolved experiments described here confirm that the internal currents greatly affect the distortion even in the absence of a particle flow outside the drop.

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FIGURE CAPTIONS

Figure 1: (a) Photograph of strain-confined electron-hole drop in a 4 mm × 4 mm × 2 mm crystal of ultra-pure dislocation-free Ge (Sample CR37). (b) Calculated lines of constant electron-hole liquid (EHL) energy in a square Ge sample which is stressed at the top by a nylon plunger with 9 kg force. The plunger has a 6 mm radius of curvature. The applied stress direction is ⟨111⟩. This strain pattern is obtained from a finite-element computer analysis [3]. The EHD is confined to the point of shear strain maximum.

Figure 2: Numerical calculation of the EHL energy shift for the geometry of Figure 1b and an applied magnetic field H = 50 kOe along the $\langle 11\bar{2} \rangle$ crystal axis.

Figure 3: (a) Drawing of the crystal mounting and orientation. Both a face and edge view are observed. (b) Image from the infrared vidicon showing a single EHD within the crystal. Laser power is 50 mW absorbed into the crystal, T = 1.7 K, and the contact force is ≈ 9 kg. (c) Distortion in drop shape when $H \,||\, \langle 11\bar{2} \rangle$ axis. (d) Distortion in drop shape when $H \,||\, \langle 1\bar{1}0 \rangle$ axis. Sample CR37

Figure 4: Field dependence of the drop distortion for 9 kg applied force. $R_{\parallel}$ is the EHD dimension along H and $R_{\perp}$ its dimension perpendicular to H. These data correspond to the geometry of Figure 3d. $P_{abs} \approx 90$ mW. Sample CR38

<u>Figure 5</u>: Field dependences of the drop distortion for two values of applied force, 4.5 kg and 18 kg. The distortion is more pronounced for the smaller stress. As in Figure 4, H is along the ⟨1$\bar{1}$0⟩ axis. $P_{abs} \approx 3$ mW. Sample CR38

<u>Figure 6</u>: Weak dependence of the EHD luminescence decay time as a function of H. $P_{abs} \approx 3$ mW; applied force = 9 kg. Sample CR38

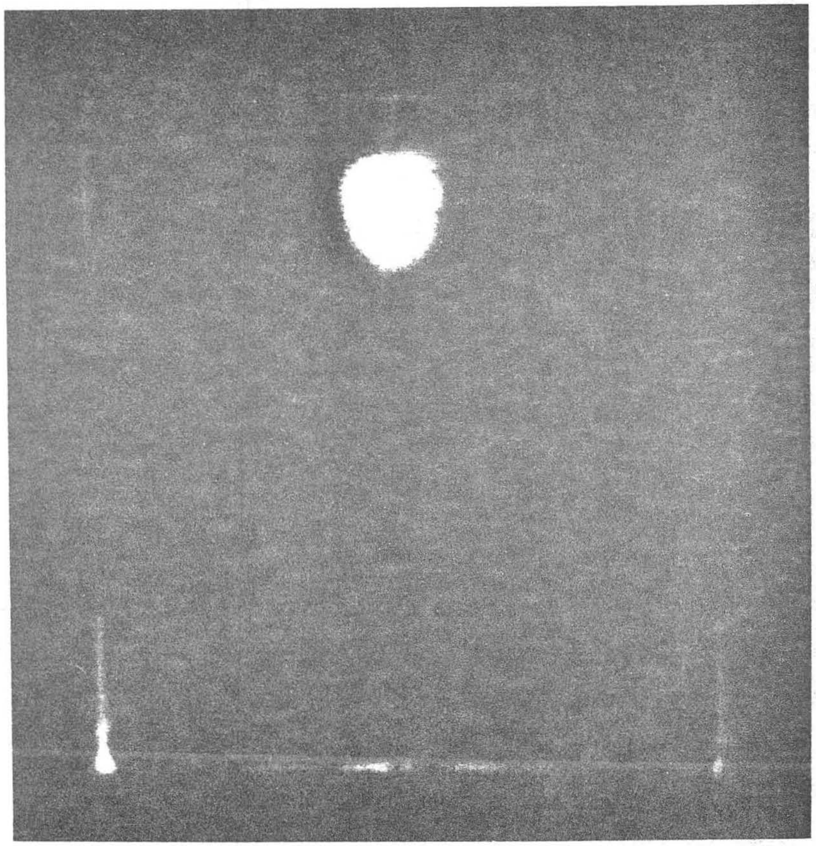
<u>Figure 7</u>: Field dependence of the drop distortion for the same experimental conditions as in Figure 4, except $P_{abs} \approx 3$ mW. The drop distortion is present, even though the radius is smaller than the saturation value of ≈ 300 μ for $R_{\parallel}$ in Figure 4. Sample CR38

<u>Figure 8</u>: (a) Diagram of stress and field directions for H || ⟨001⟩ experiment. (b) Image of the drop luminescence in zero magnetic field. $P_{abs} \approx 50$ mW. (c) Change in shape observed when a 20 kOe field is applied along the ⟨001⟩ axis. The sample was permanently stressed, as discussed in [3]. Sample CR36

<u>Figure 9</u>; (a) Schematic diagram showing recombination currents of electrons (solid arrows) and holes (dashed arrows) in zero magnetic field. (b) Modification of these drift currents caused by the Lorentz forces in an applied field (assumed parallel to the z-axis). A net circulating current results. (c) Hypothetical schematic of a non-radial distribution of recombination currents resulting from an anisotropic flow of carriers to the drop surface. Zero field. (d) Similar to (c), but in a nonzero field. In this case the induced electric current produces a <u>diamagnetic</u> magnetization.

Figure 10: Change in drop shape observed as the laser spot is translated. A magnetic field is applied along the stress direction. Laser position is (a) 0.5 mm, (b) 0.9 mm, (c) 1.1 mm, (d) 1.5 mm from the stressed crystal surface, defined by the bright horizontal line. All these drops are observed to be cylindrically symmetric about the field direction. Sample CR37

Figure 11: Time resolved decays of the EHD in a magnetic field $H = 20$ kOe $\|$ $\langle 111 \rangle$ for two different initial drop shapes. The light ($P_{abs} = 90$ mW) is switched off at $t = 0$ and a time resolved slit scan gives the EHD dimensions parallel ($R_{\|}$) and perpendicular ($R_{\perp}$) to the field. (a) Laser excitation as in Figure 10a, (b) Laser excitation as in Figure 10d.



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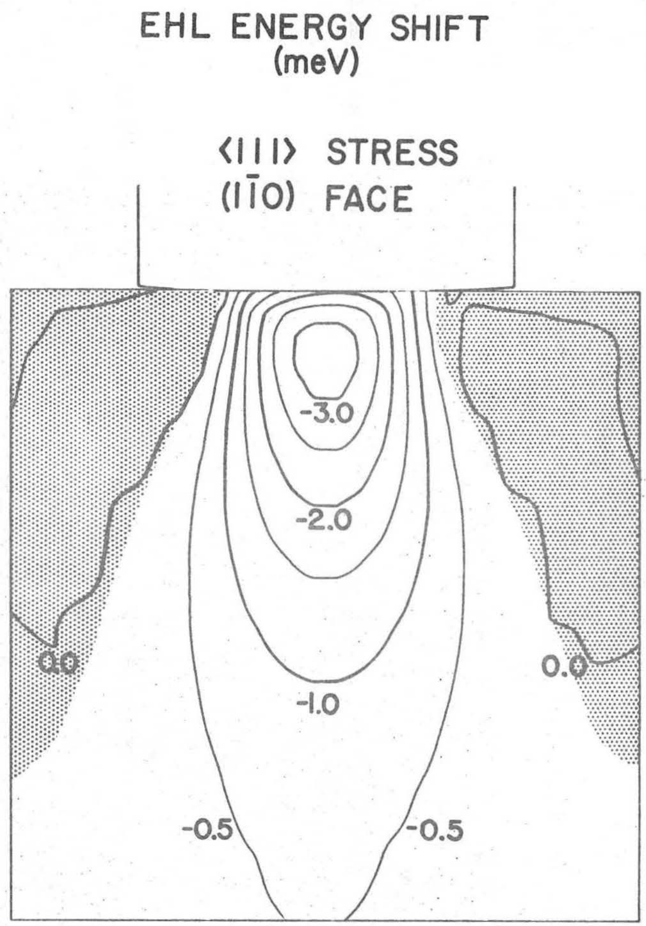
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(b)

Fig. 1

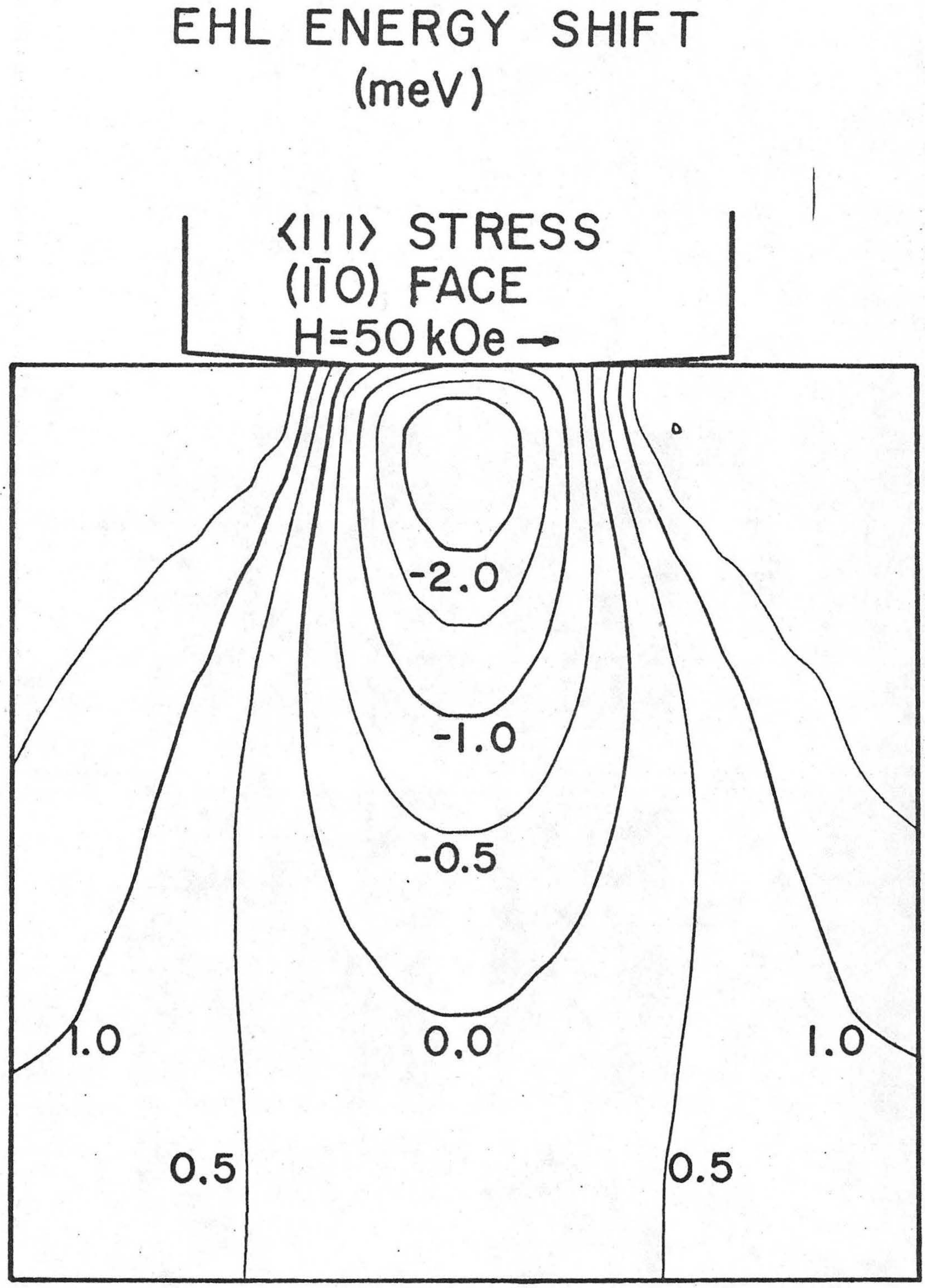

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Fig. 2

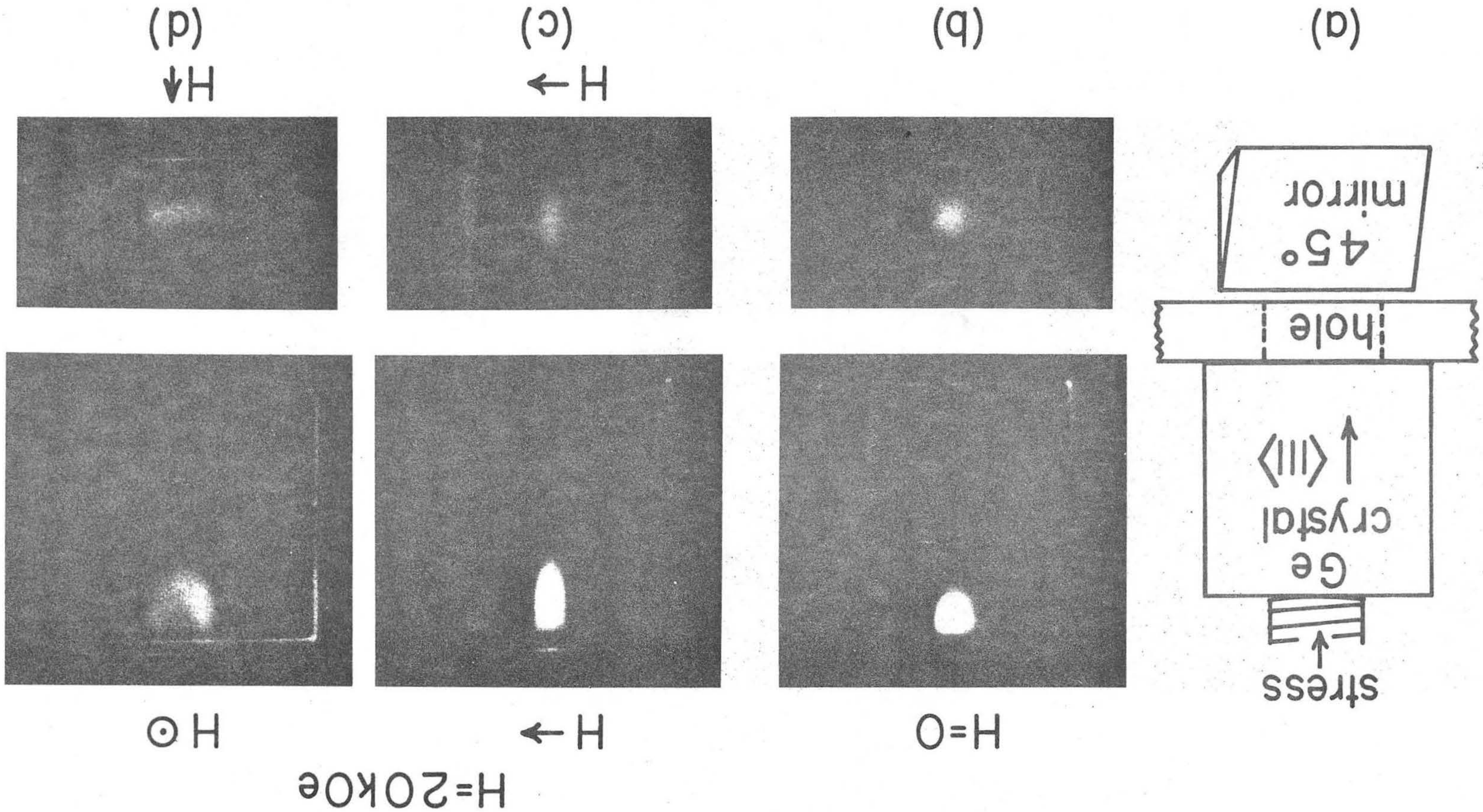

Fig. 3

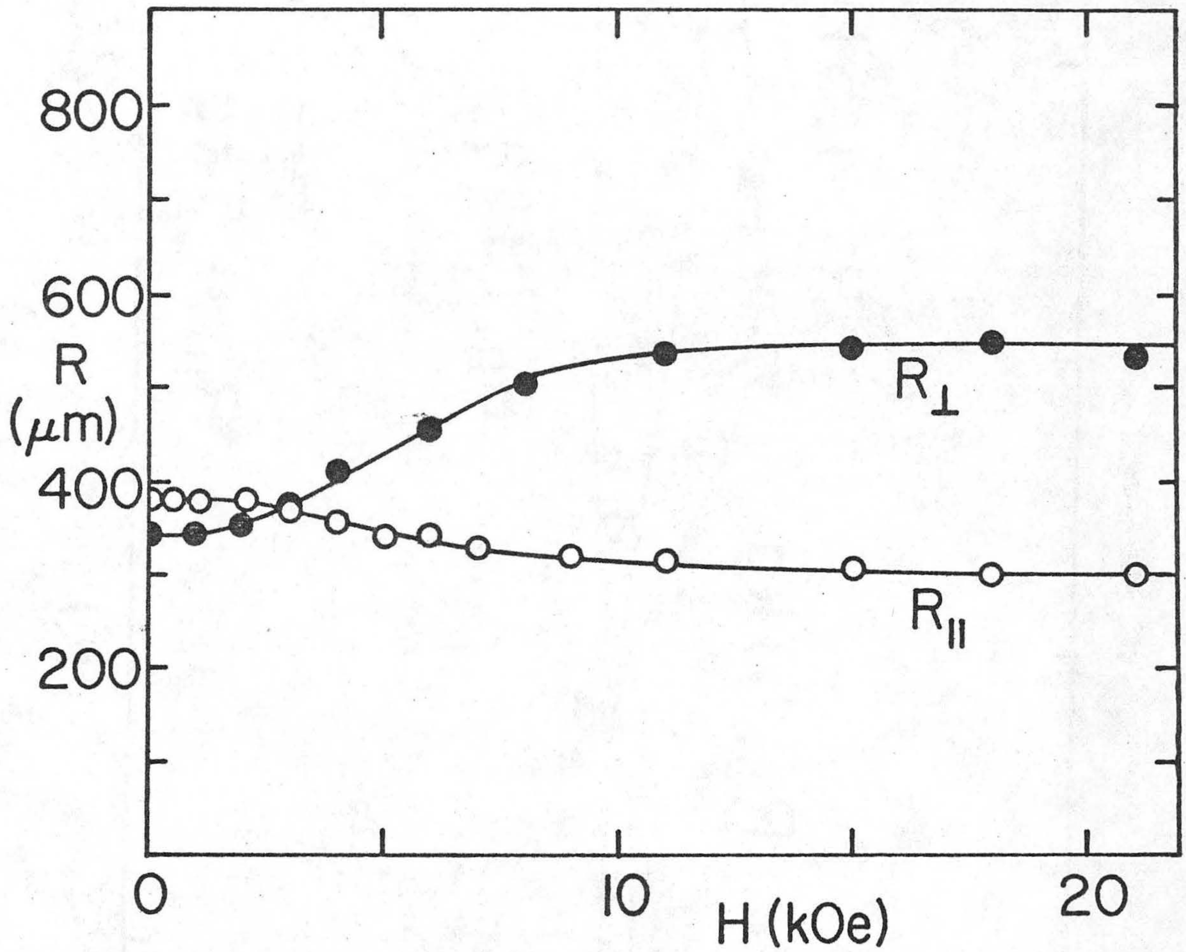

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Fig. 4

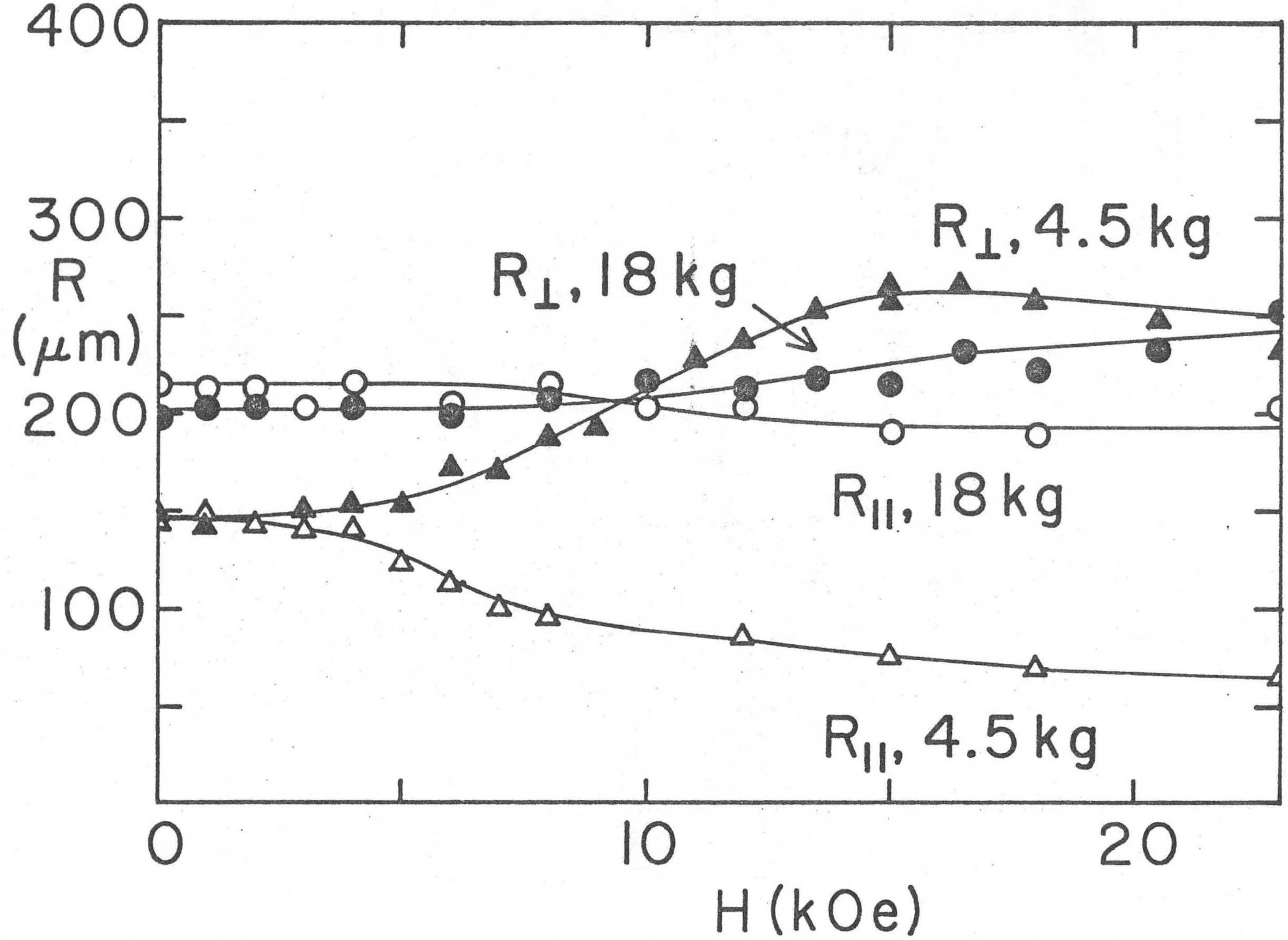

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Fig. 5

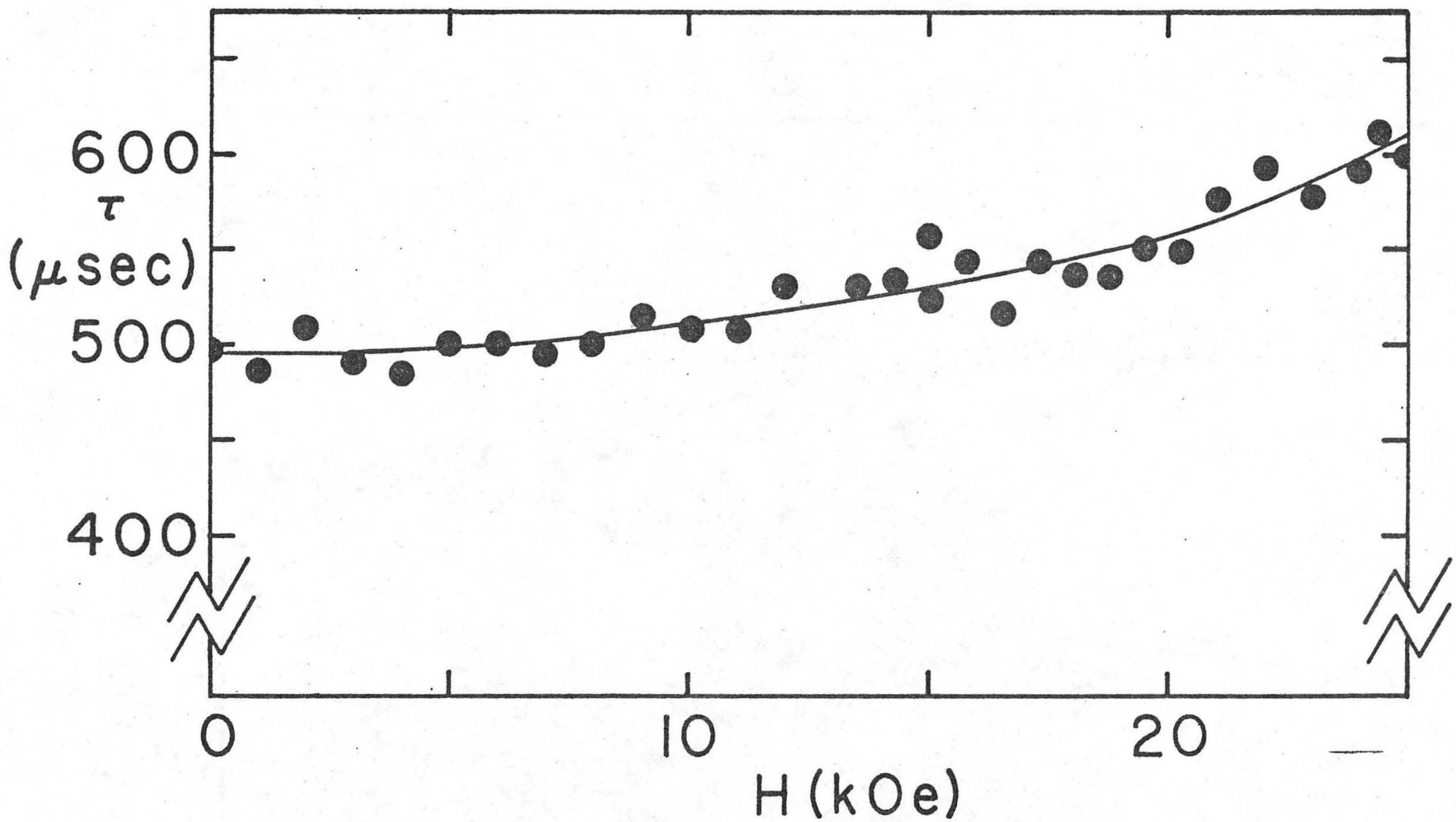

Fig. 6

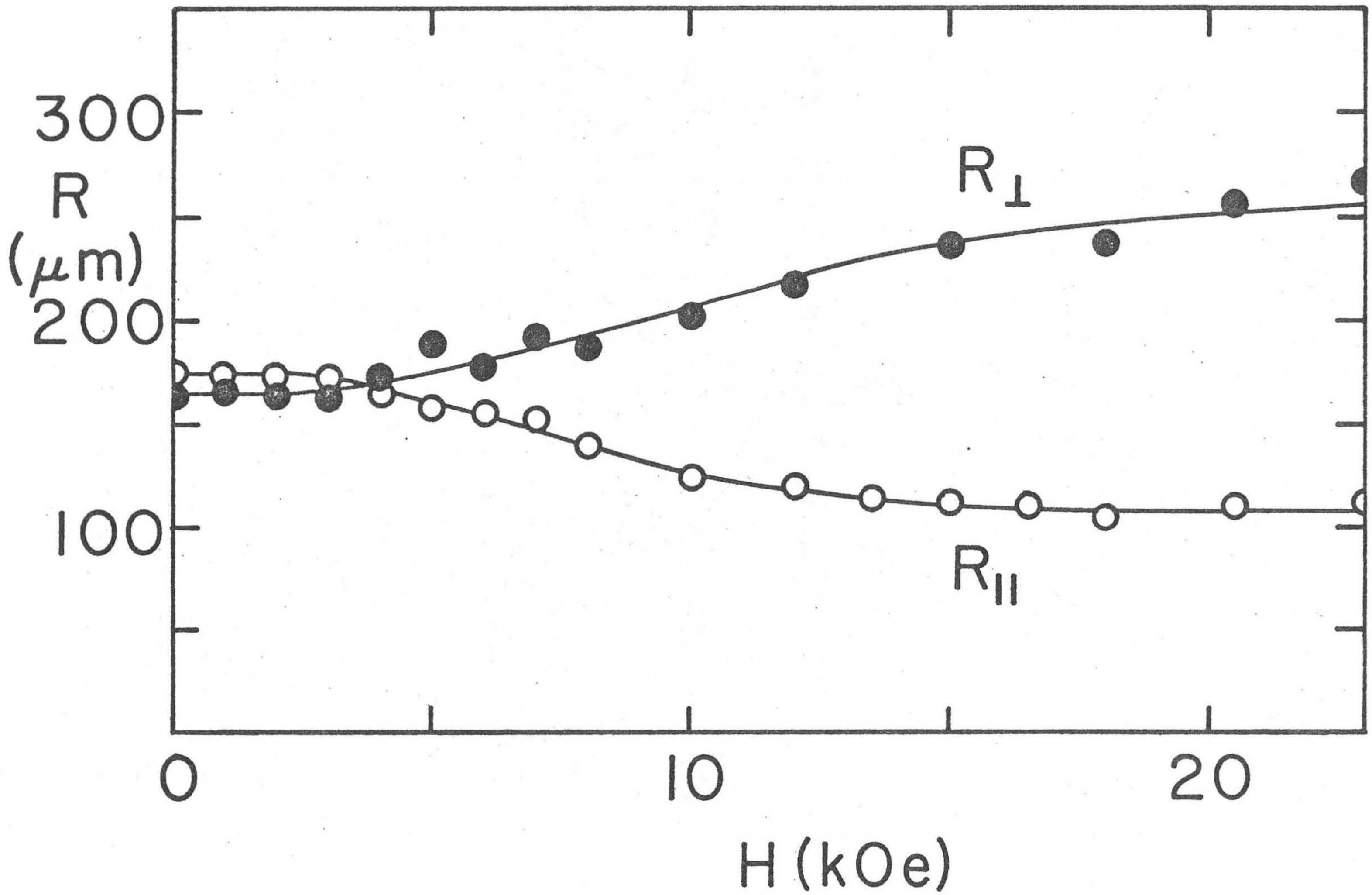

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Fig. 7

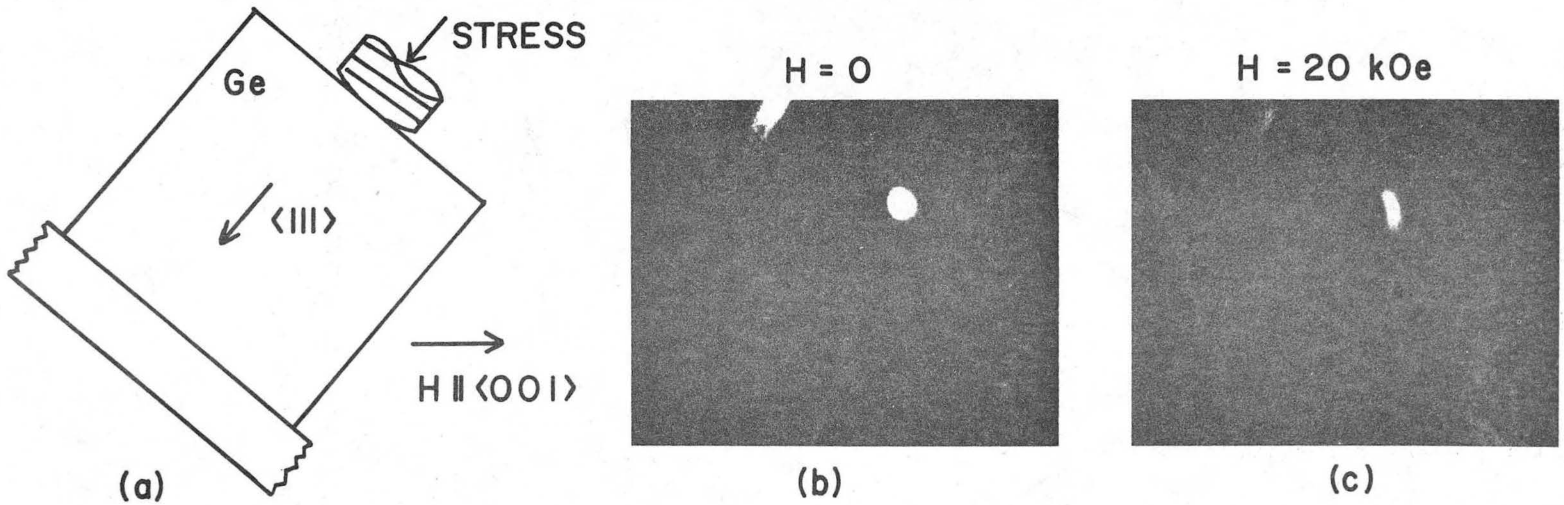

Fig. 8

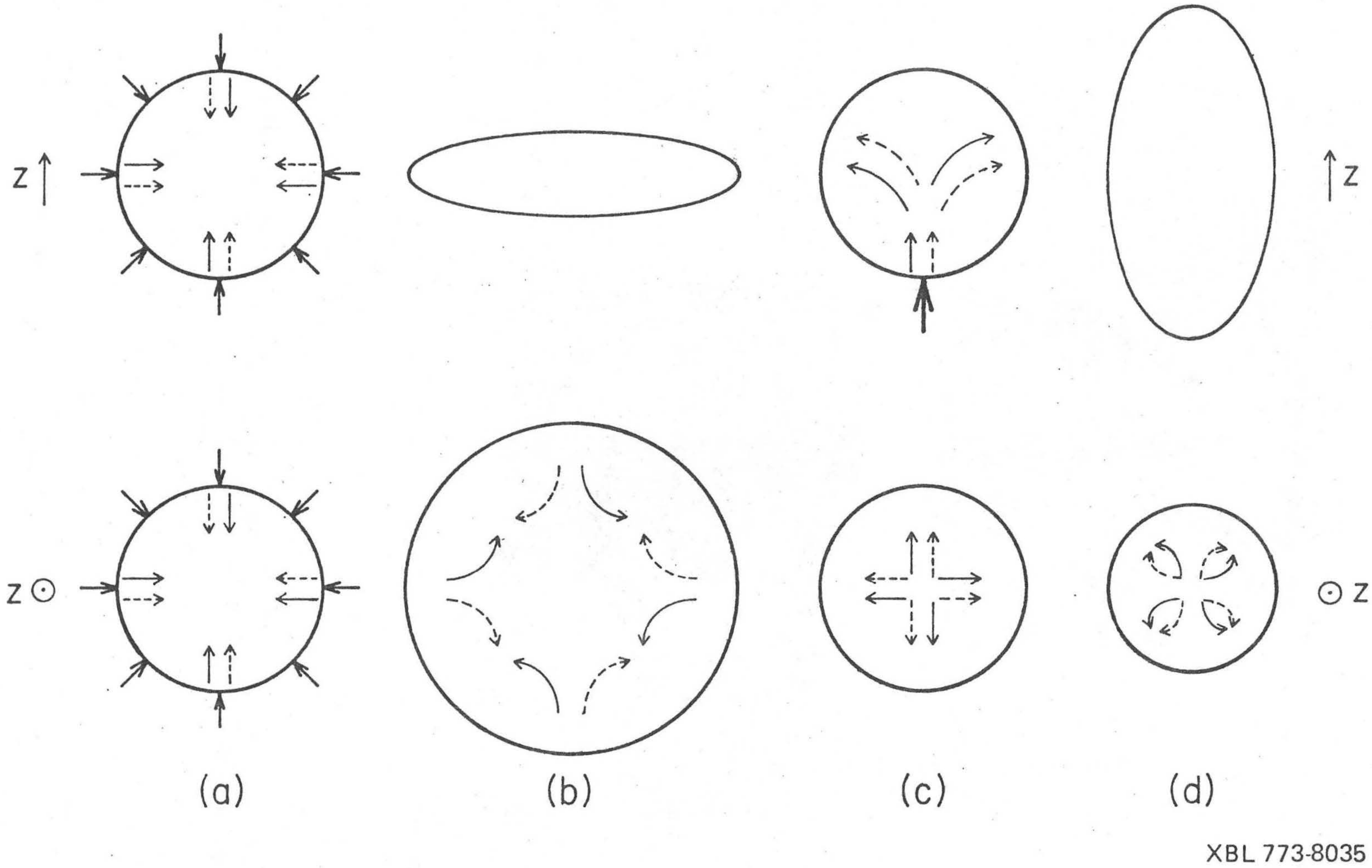

Fig. 9

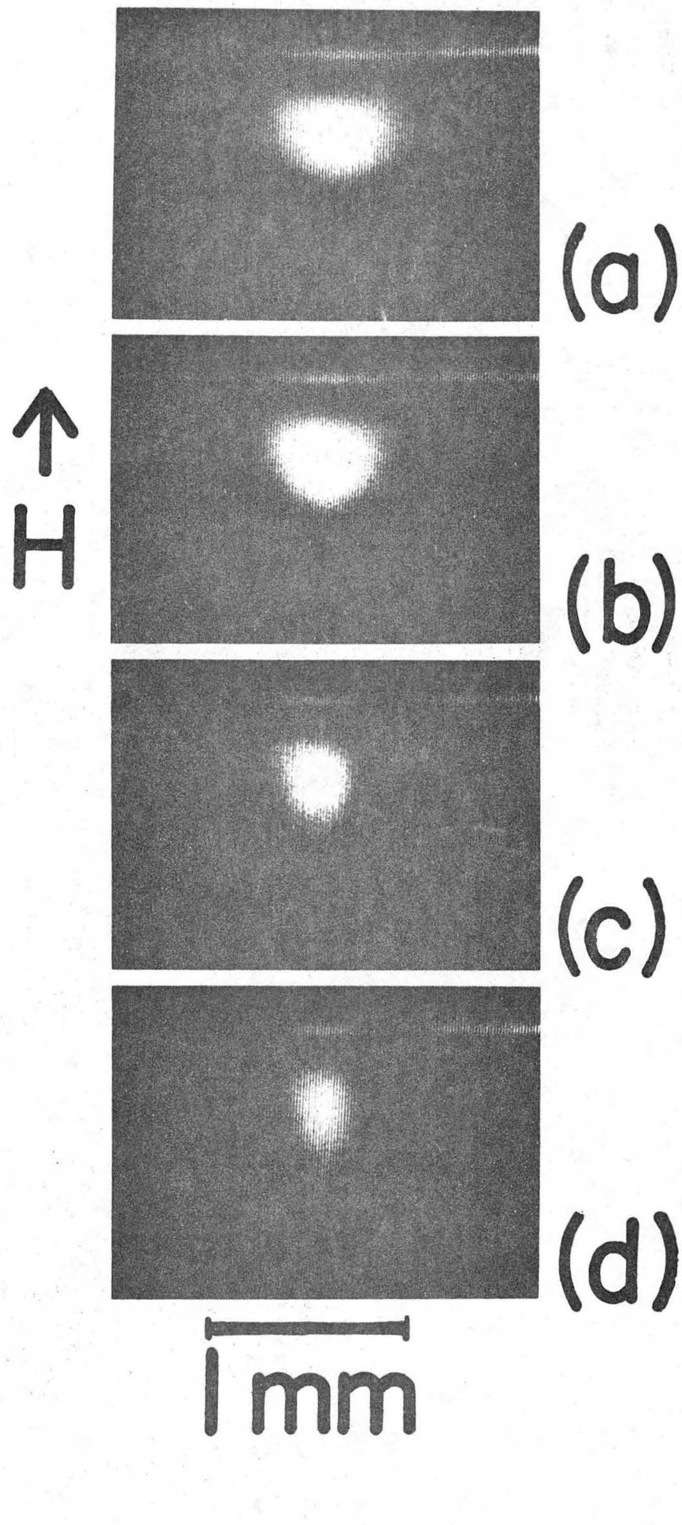

Fig. 10

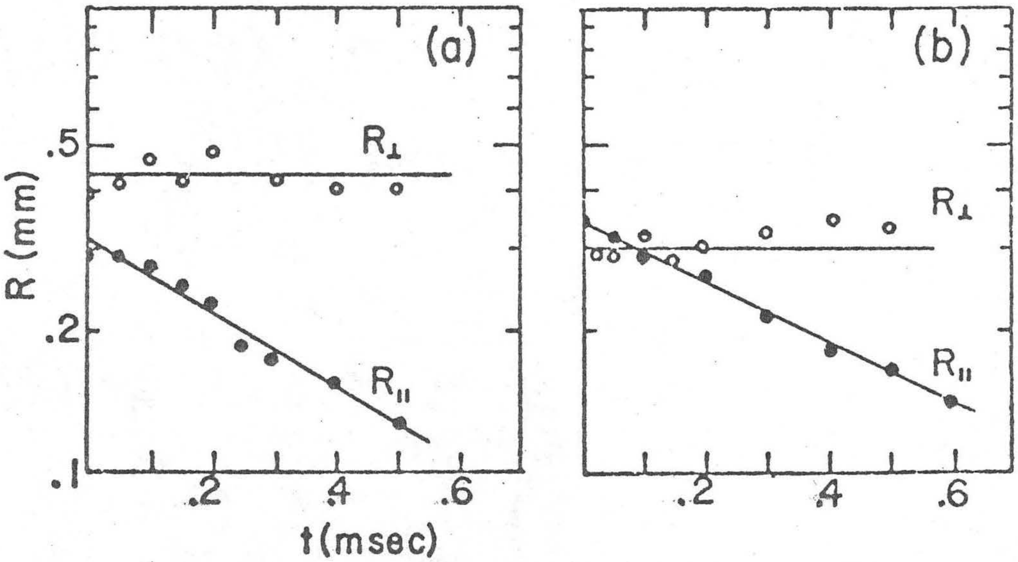

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Fig. 11

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