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Infrared Absorption at 10.6 μ in GaAs

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TABLE I. Temperature 25°C.

λ (μ)	($\nu = 1/\lambda$) $\times 10^{-4}$ cm^{-1}	n^e	n^0
0.62	1.6129	3.2560	2.9028
0.65	1.5385	3.2064	2.8655
0.68	1.4706	3.1703	2.8384
0.70	1.4286	3.1489	2.8224
0.80	1.2500	3.0743	2.7704
0.90	1.1111	3.0340	2.7383
1.00	1.0000	3.0050	2.7120
1.20	0.8333	2.9680	2.6884
1.40	0.7143	2.9475	2.6730
1.60	0.6250	2.9344	2.6633
1.80	0.5556	2.9258	2.6567
2.00	0.5000	2.9194	2.6518
2.20	0.4545	2.9146	2.6483
2.40	0.4167	2.9108	2.6455
2.60	0.3846	2.9079	2.6433
2.80	0.3571	2.9052	2.6414
3.00	0.3333	2.9036	2.6401
3.20	0.3125	2.9017	2.6387
3.40	0.2941	2.9001	2.6375
3.60	0.2778	2.8987	2.6358
3.80	0.2632	2.8971	2.6353
4.00	0.2500	2.8963	2.6348
5.00	0.2000	2.8863	2.6267
6.00	0.1667	2.8799	2.6233
7.00	0.1429	2.8741	2.6156
8.00	0.1250	2.8674	2.6112
9.00	0.1111	2.8608	2.6066
10.00	0.1000	2.8522	2.6018
11.00	0.0909	2.8434	2.5914

described[3] with the addition of a thermocouple detector and a Perkin–Elmer Nernst glower as a source and a 30-cps mechanical chopper for use at wavelengths of 4 μ and longer.

The specimen, being somewhat rare and not overly large was made into a prism of angle 14°10′24″. The optic axis lies in one of the faces since the natural shape favored this. To put the optic axis in the median plane would have greatly reduced the size of the resultant prism. This surface containing the optic axis was made normal to the beam from the monochromator by means of an autocollimating eye piece. The prism axis was then locked and kept locked during the run. The optic path in the crystal is thus the same as it would be with a prism having the optic axis in the median plane but the angles are just half as large. It might be called a half prism in terms of minimum deviation prisms of birefingent crystals. Deflections were read as angles from the main beam. The results are given in Table I. The data are no better than three digits past the decimal up to 4 μ. Past there, the fourth digit may have some significance.

Prior to the work reported here and in Ref. 1 the best refractive-index data available was that of Rose[4] between 0.5985 and 0.762 μ. Our indices are higher by approximately 0.02 over the comparable range with that of Rose. The birefringence is reasonably close. When compared with the recent results reported by Martin and Thomas[1] we again find our indices higher by approximately 0.02 in the visible and near infrared but with our indices becoming lower than theirs past 0.83 μ by a maximum of approximately 0.07 over the range of 4–11 μ. The birefringence agrees quite closely over the full range.

Transmission measurements show a strong absorption at wavelengths less than 0.63 μ or greater than 13.5 μ. A strong absorption peak occurs at 15.0 μ. It may be that our material has higher absorption at short wavelengths than that of the previous investigators[1,4] since they obtained data at shorter wavelengths than we found possible. X-ray data indicated the crystal was highly strained. The point group of HgS is 32 (D_2) as is quartz, and consequently, right or left rotation of growth is possible as well as intergrowth.

We wish to thank A. Ashkin and K. Nassau for their interest in this work.

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Infrared Absorption at 10.6 μ in GaAs*

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It has recently been shown that GaAs has a large electro-optic coefficient at 10.6 μ and is thus a promising material for modulation of light from CO_2 lasers.[1] Since hundreds of watts are available for modulation from such lasers, even a small fractional absorption can cause considerable heating in the modulator. By measuring the residual infrared absorption in samples of GaAs with resistivities higher than 10^4 Ω·cm, we have determined that in such samples the fraction of incident light intensity absorbed at 10.6 μ is 0.006 ± 0.002/cm. This low absorption indicates that high-resistivity GaAs is suitable for modulation of high-power CO_2 laser light.

With the advent of lasers providing the order of watts output in a well-collimated beam, small-energy absorptions can be measured calorimetrically. A previous technique using the thermal lens effect[2] is sensitive to absorptions of 10^{-4}/cm, but it is somewhat more difficult to apply with CO_2 lasers. On the other hand, direct calorimetric measurements are very simple and give a sensitivity of 10^{-3}/cm when employed with lasers with a power of a few watts. The temperature rise in six samples of GaAs with resistivities varying from 10^4 to 10^9 Ω·cm was measured when the samples were subjected to a known amount of CO_2 laser radiation. The rise in temperature was converted to energy absorbed using the known specific heat of GaAs.[3] All samples had the same absorption coefficient 0.006 ± 0.002/cm. The error in these measurements was attributed to systematic effects such as residual dirt on the sample, heat transfer from neighboring objects, etc. The noise in our measurements was about 5%. The same coefficient was obtained when the sample thickness was changed by a factor of 20, indicating that a true volume absorption was measured.

Since we found the absorption at 10.6 μ in GaAs was independent of resistivity from 10^4–10^9 Ω·cm, it is clear that free-carrier absorption is not important at these low carrier concentrations. From an extrapolation of absorption measurements on low-resistivity GaAs,[4] it is expected that the free-carrier absorption in GaAs will be less than 0.6%/cm as long as the number of carriers is less than about 10^{13}/cc. This corresponds roughly to a resistivity of 10^8Ω·cm. Thus, our measured independence of absorption on carrier concentration for resistivities in the range 10^4 Ω·cm and higher is to be expected. To eliminate absorption due to free carriers, material suitable for modulation of CO_2 laser light should have resistivities about 10^4 Ω·cm or higher. Since the fundamental GaAs lattice absorption occurs near 36 μ, the measured residual absorption of 0.006/cm is probably due to the tails of the fundamental lattice absorption.

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Electrical Conductivity and Hall Effect in Thin Vanadium Films

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Thin vanadium films were prepared by evaporating spectroscopically pure vanadium metal (obtained from Johnson, Matthey & Co., London) at room temperature and at a pressure of 1×10^{-5} Torr onto well-cleaned and dried glass microslides in an Edwards high-vacuum coating unit model 12EA. Precise determinations of the thicknesses were made colorometrically by dissolving the metal from the known area of the substrate in dilute HNO_3 and sodium carbonate and employing the 8-hydroxyquinoline method[1] for estimating the amount of the metal. The thickness was calculated from the mass determined in this manner, using the known bulk density of vanadium. The accuracy of the thickness measured is about 5% for 50–100 Å thickness range and better for thicker films. Contacts were made by soldering copper wires with indium metal on the silver or gold electrodes. The dc Hall voltage was measured using a Tinseley vernier potentiometer, type 4363-D, having a least count of 0.1 μV.

The Hall voltage E_H was found to vary linearly with the magnetic field H and the current I for all thicknesses. In Fig. 1 (curve 1) we have plotted the Hall coefficient R_H as a function of thickness. The Hall voltage increases rapidly with decreasing thickness below 300 Å. The value of the Hall coefficient for larger thicknesses is smaller by about 15% than the value $R_H=8.13\times10^{-13}$ $V\cdot cm\cdot A^{-1}\cdot G^{-1}$ found by Foner[2] for bulk vanadium. The sign of the Hall coefficient is positive for all thicknesses, implying a predominantly hole mechanism of conduction. Curve 2 shows the plot between the resistivity and thickness. The resistivity also increases rapidly with decreasing thickness below 300 Å. However, even at larger thicknesses (572 Å) the resistivity is three times that of the bulk metal.[3] The fact that the resistivity of the films is much larger than that of the bulk metal may indicate the presence of structural imperfections in the films.[4] By fitting our data on the Hall effect with Sondheimer's equations,[5] we estimate a bulk mean free path of about 600 Å. The resistivity data, however, imply on the same model a larger mean free path of about 1000 Å. Neither of these values can be trusted to any accuracy, since the free-carrier model may not be applicable[6] to the vanadium thin films. It seems that the smaller value of mean free path (which seems to be the more realistic of the two for transition metals)[7] is probably the better estimate. The Hall mobility μ_H, which is the ratio of the Hall coefficient and the resistivity, is shown as a function of thickness by curve 3 in the same figure. The Hall mobility decreases with the decrease in the thickness. Such a decrease in the Hall mobility is to be expected on the basis of Sondheimer's model[6] of the influence of size effects on the electrical properties of thin films. Sondheimer predicts that the increase in resistivity with decreasing thickness is faster than the increase in the Hall coefficient. Physically, this result is understandable because we expect the mobility to decrease with the decreasing effective mean free path (determined by the thickness and possibly by the granule size when the thickness and the granule size are smaller than the bulk mean free path).

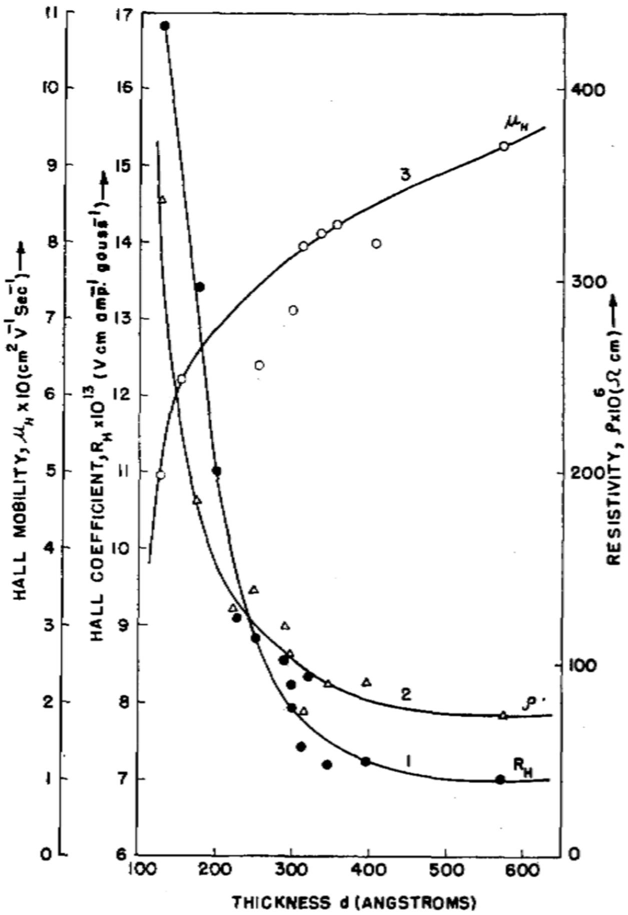

FIG. 1. The variation of Hall coefficient R_H, resistivity ρ, and Hall mobility μ_H with film thickness.

The Hall mobility increases on heating the film for about 2 h at temperatures below 250°C and then decreases at higher temperatures. As for freshly prepared films, a linear Hall-voltage dependence on the magnetic field was observed in the case of thermally treated films. The increase in Hall mobility on aging below 250°C seems to indicate the annealing of structural defects due to heat treatment. This is supported by the observation that, on aging films of thickness greater than 150 Å at room temperature for 24 h, the resistivity decreases by several percent. It is possible that by annealing films thicker than those used here at low temperatures, the resistivity will appreach the bulk value more closely.

On heating the films to higher temperatures there is an irreversible rise in resistance, an increase in the Hall coefficient, and a decrease in Hall mobility, presumably due to the fact that a substantial part of vanadium is now oxidized.

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