NEW TYPE OF PHOTOCONDUCTION IN n-CdS*

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Abstract

Four strong resonances have been observed in the far-infrared transverse magnetophotoconductivity of n-CdS at 1.2 and 4.2K. The resonances are observed in the spectral range $10\text{--}120\text{ cm}^{-1}$ at fields to 90 kOe. Two of these resonances are observed as a direct consequence of optical phonon emission and thus represent a new type of photoconductivity.

Four strong resonances have been observed in the far-infrared (FIR) photoconductivity of n-CdS at low temperatures and high magnetic fields. Two of these resonances have previously been observed in n-CdS in the FIR transmission experiments of Cohn et al¹; the observation of these resonances in photoconductivity is probably associated with the conventional photothermal ionization mechanism for hydrogenic donor states. A third resonance is due to cyclotron-phonon absorption; this process has previously been observed in n-CdS only at extremely high magnetic fields in the pulsed-field transmission experiments of Nagasaka et al². The fourth resonance has never been observed before in n-CdS and is due to an absorption process in which two phonons are emitted. The observation of these last two absorption processes as photoconductivity resonances represents a new form of photoconduction in which the conductivity is modulated by the phonons emitted in optical absorption instead of the electronic excitation.

1. EXPERIMENTAL DETAILS AND OBSERVATIONS

The FIR photoconductivity of two samples of n-CdS was measured in magnetic fields to 90 kOe and in the spectral range 10-120 cm^{-1} . The spectra were obtained using both Michelson and lamellar Fourier transform spectrometers described previously³. The n-type CdS samples had a net carrier concentration of $7.1 \times 10^{15} \text{ cm}^{-3}$. The samples were plates of area $6 \times 6 \text{ mm}^2$ and were .7 and 1.7 mm thick; the c-axis of the material was aligned normal to the faces of the plates. Photoconductivity was observed in the Faraday geometry in which both the incident radiation and the magnetic field were parallel to the c-axis. The sample conductivity was measured at a bias voltage of 10 V/cm across the face of the sample.

The samples were cooled by immersion of the sample insert in liquid helium; sample temperatures of 1.2K were obtained by pumping the helium bath. A 1.5 mm thickness of LiF (Reststrahlen absorption from $308\text{--}637\text{ cm}^{-1}$) and a black polyethylene sheet were employed as cold filters; thus background radiation as high as 300 cm^{-1} was incident on the sample. This radiation may account for the unexpected observation of free polaron phenomena in the present experiments at 1.2 and 4.2K. Photoconductivity spectra were obtained at higher frequencies and will be discussed in a subsequent publication.

Four of the photoconductivity spectra measured at 4.2K are shown in Fig. 1. Three distinct lines labeled M, L, and K are observed at lower field values; in addition a very broad threshold resonance (labeled S in the figure) is present in all the photoconductivity spectra.

Figure 2 presents photoconductivity spectra for 60 kOe at 1.2 and 4.2K; the spectra have been normalized to the threshold photoconductivity S. Relative to this threshold the line M strengthens at higher temperatures while L and K are observed to weaken.

2. OPTICAL ABSORPTION PROCESSES

In discussing the four photoconductivity resonances which have been observed it is essential to distinguish between the absorption process responsible for an excitation of CdS and the mechanism by which the excitation subsequently exerts an influence on the material's conductivity. Figure 3 is a composite plot exhibiting the photoconductivity resonance frequencies observed as a function of magnetic field. The photoconductivity resonances M and S correspond to the strong absorption seen previously by Cohn, et al¹. Recently Simmonds, et al⁴, have suggested that the absorption processes are associated with excited state transitions of the conventional hydrogenic donor which is known to exist in n-CdS with a binding energy of 240 cm^{-1} ^{5,6}; the observation of these processes as conductivity resonances would then be due to the conventional photo thermal ionization mechanism.

The remaining lines, K and L, have not been observed previously in the magnetic field regime of this experiment. The position of the resonance K is independent of magnetic field and occurs at 86 cm^{-1} ; this value is exactly twice the frequency of the infrared inactive $43 \text{ cm}^{-1} \Gamma_6(E_2)$ phonon in CdS. The Raman activity of this phonon has been studied by Arguello, et al⁷; the pinning of the polaron cyclotron resonance by this phonon has also been observed in FIR absorption experiments at 19 and 38 K⁸. The details of the absorption process responsible for this apparent two-phonon photoconductivity are unknown; the process presumably involves the emission of two phonons in an electron-mediated second-order magnetophonon resonance similar to first-order processes discussed in the literature⁹. The phonon-induced modulation of the electrical conductivity is best discussed in conjunction with the fourth photoconductivity resonance, L.

The frequency of L is exactly the sum of the polaron cyclotron resonance (CR) frequency and the 43 cm^{-1} phonon frequency. This combination of frequencies is expected for the process of cyclotron-phonon absorption which has been observed by several authors in optical absorption experiments including one with n-CdS^{10,11,12}. Cyclotron-phonon absorption is due to a second-order process in which a single photon is absorbed while a carrier is excited to the next highest Landau sub-band and an optical phonon is simultaneously emitted; this absorption process is resonant for the emission of optical phonons with very small quasimomenta¹⁰.

3. NEW PHOTOCONDUCTIVITY MECHANISM

In absorption experiments cyclotron-phonon absorption is invariably observed in conjunction with substantially stronger absorption at the fundamental free-carrier cyclotron frequency. The hallmark of the present photoconductivity experiments is the absence of any trace of this cyclotron frequency absorption in the conductive response of the material. Photoconductivity resonances at the free-carrier cyclotron frequency have been observed in n-InSb and several

other materials⁵. In these cases the conductive response is due to the energy dependence of the carrier mobility in the material; narrow band-gap and other materials with substantially non-parabolic carrier dispersion relations are favorable for observation of this photoconductivity mechanism. The absence of a photoconductivity resonance at the cyclotron frequency excludes this mechanism as an explanation for the K and L resonances in n-CdS; inasmuch as CdS has a highly parabolic dispersion relation this absence is not unexpected. The conductive response observed as the K and L resonances is thus clearly associated with the emission of the 43 cm^{-1} phonon in the absorption process and not to any concomitant electronic excitation. In the case of the L resonance due to cyclotron-phonon absorption the electronic excitation is in fact incidental to the conductive response observed.

An understanding of the nature of electron-phonon scattering for optical phonons at high magnetic fields is essential to the explanation of this strong optical phonon enhancement of the magnetoconductivity in n-CdS. Experimental results pertinent to this process are scant. Photoconductivity associated directly with the emission of optical phonons has not previously been observed in any material. Photocarrier magnetoresistance measurements have been made on CdS,¹³ but the absence of a sizable thermal population of the 43 cm^{-1} phonon at low temperatures and the relatively low magnetic fields employed (20 kOe) would obscure the influence of this phonon on the high-field magnetoconductivity.

A simple theoretical argument, however, is capable of explaining the role of the non-thermal 43 cm^{-1} phonons in enhancing the conductivity of n-CdS. These phonons are zone-center phonons with small quasimomenta; thus the first-order channel for an electron-phonon scattering event in which the phonon is destroyed can proceed only when the phonon energy is equal to a multiple of the Landau level spacing. Away from this field region a second-order channel in which the electron and phonon scatter off each other quasi-elastically can

be expected to dominate the scattering process. This quasielastic electron-phonon scattering provides a mechanism for the observed enhancement of the conductivity. The effect of this scattering is indicated by a remarkable expression relating the electrical conductivity of a material in the high-field region to the diffusivity of its carriers as a result of elastic scattering events¹⁴. This high-field region is characterized by the expression $\sigma_{xx} \ll \sigma_{xy}$, where σ_{ij} is a component of the conductivity tensor and the magnetic field is assumed to lie in the z-direction. Under these conditions the conductivity transverse to the magnetic field can be expressed in terms of the migration of the center of a carrier's cyclotron orbit. The conductivity is in fact enhanced by elastic scattering events and is linearly related to the mean square displacement of this center in the plane perpendicular to the field.

In summary a new type of photoconductivity has been observed which is associated directly with the emission of phonons in an optical absorption process. The photoconductivity is observed only at relatively large magnetic fields (≥ 20 kOe). A simple theoretical argument is capable of explaining this photoconductivity mechanism, but further experimental and theoretical work will be required to unequivocally account for the observed phenomena.

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Figure Captions

- Figure 1 Photoconductivity spectra observed at 4.2K for four typical magnetic fields. The magnetic field was parallel to the c-axis of CdS.
- Figure 2 Photoconductivity spectra observed at 1.2K and 4.2K. The magnetic field was 60 kOe.
- Figure 3 Composite plot of the photoconductivity resonance frequencies observed as a function of magnetic field. The dashed line represents the location of cyclotron absorption. The solid horizontal lines at 43 and 86 cm^{-1} indicate the energies associated with one and two Γ_6 43 cm^{-1} phonons. The solid line parallel to the dashed line indicates the energies at which cyclotron-phonon absorption occurs.

Figure 1

Figure 2

Figure 3