phys. stat. sol. (a) 75, 405 (1983)

Subject classification: 7 and 14.3.4; 22.4.2

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Electro-Acoustic Effects in CdSe

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An investigation is made of the electro-acoustic current saturation, electro-acoustic current noise, and electro-acoustic effects in the ac impedance for a single crystal of hexagonal n-type CdSe. The electric field is applied along the *c*-axis. The experimental data are interpreted in terms of a previously published theory. It is concluded that the experimental data for CdSe are described very well by this theory. The experimental results for CdSe are similar to previously published results for CdS.

Electro-akustische Stromsättigung, elektro-akustisches Stromrauschen und elektro-akustische Effekte in der elektrischen Impedanz werden in einem hexagonalen n-Typ CdSe-Kristall untersucht. Die experimentellen Daten werden mit Hilfe einer früher veröffentlichten Theorie interpretiert. Die experimentellen Ergebnisse für CdSe stimmen sehr gut überein mit dieser Theorie. Die Ergebnisse für CdSe sind früher veröffentlichten Ergebnissen für CdS ähnlich.

1. Introduction

For many years now electro-acoustic effects have been a subject of continuous interest [1, 2].

Recently we reported an extended set of experimental data on electro-acoustic current saturation [3, 4], electro-acoustic current noise [5], and electro-acoustic effects in the ac impedance [3, 4] for single crystals of hexagonal n-type CdS. In the samples the amplified acoustic flux originated from the thermal background. For the description of the observed effects we made use of a theoretical model, which took into account the trapping and detrapping of groups of free charge carriers in deep potential troughs [6]. These potential troughs are associated with the amplified acoustic waves and hence are moving with the velocity of sound. Charge carriers in the conduction band may either be trapped in such potential troughs, and, accordingly, are forced to move with the sound velocity, or be free moving with the carrier drift velocity.

Such a potential-trough model was first suggested in 1962 by Rose in a paper by Smith [7]. In 1967 Moore used such a potential-trough model to describe electro-acoustic current fluctuations [8]. In [6] we gave in a local description an extended potential-trough model.

In this paper we report experimental data on electro-acoustic current saturation, electro-acoustic current noise and electro-acoustic effects in the ac impedance for a single crystal of hexagonal n-type CdSe (obtained from Eagle Picher Ind., Inc.).

2. Current Saturation

A CdSe sample (resistivity $\approx 0.04\ \Omega$m) was supplied with two ohmic In-contacts [4] in such a way that the electric field was parallel to the *c*-axis. The contact spacing was 1.88×10^{-3} m and the contact area was $(2.62 \times 10^{-3}) \times (0.36 \times 10^{-3})\ \text{m}^2$. Because of the crystallographic similarity of CdSe and CdS, the electro-mechanical coupling factors, although somewhat smaller in CdSe, show similar anisotropy. All measure-

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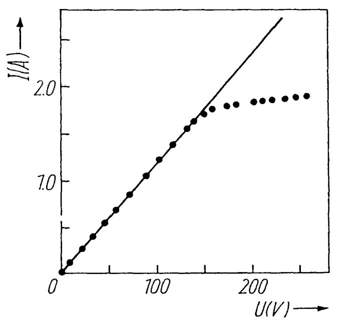


Fig. 1. Current–voltage characteristic of a CdSe sample with the electric field applied along the c-axis. The solid line represents Ohm's law

ments were carried out at room temperature. To avoid excessive Joule heating of the sample the measurements were carried out under pulsed-bias conditions (pulse duration 40 μs, pulse repetition rate 6 Hz). For further details about the experimental procedure,the reader is referred to [4, 5].

Fig. 1 shows the current–voltage (I–U) characteristic of the CdSe sample. At low voltages (below 140 V) the sample is ohmic, whereas at high voltages (above 140 V) current saturation occurs. The solid line represents Ohm's law. As in the case of CdS samples it is observed that at voltages well above the knee voltage the differential resistance is only weakly dependent on the applied voltage.

3. AC Impedance

Fig. 2 shows the absolute value of the ac impedance Z for three different applied voltages. At 72 V the ac impedance is frequency-independent and equal to the dc resistance R, as obtained from the I–U characteristic. The data at 168 and 210 V show an ac impedance plateau at high frequencies (above 3 MHz) and some structure at low frequencies (below 3 MHz). The values of the differential resistance R_d obtained from the I–U characteristic are indicated by marks on the vertical scale. According to our previously published theory [6] the ac impedance shows narrow maxima at frequencies given by

$$f = f_l = \frac{(2l+1)}{2\tau_t}; \qquad l = 0, 1, 2, 3, \dots, \tag{1}$$

where $\tau_t = L/v_{g_3}$ is the transit time of potential troughs, L the contact spacing, and v_{g_3} the component of the trough velocity, i.e. the group velocity of the amplified acoustic waves along the c-axis. The vertical marks in Fig. 2, which obviously coincide with the maxima, correspond to odd harmonics of 3.64×10^5 Hz yielding $v_{g_3} = 1.37 \times 10^3$ ms^{-1}. From this result we may conclude that transverse off-axis waves are amplified. Combining the elastic constants for CdSe given in [9] and the value of v_{g_3} we were able to determine uniquely the off-axis angle of maximum amplification. (The off-axis angle is the angle between the acoustic wave vector and the c-axis.)

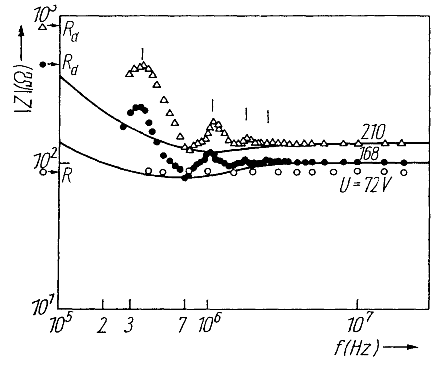


Fig. 2. The absolute value of the ac impedance Z of a CdSe sample at three different applied voltages. The values of the differential resistance R_d and the ohmic resistance R are indicated on the vertical scale. The vertical marks indicate odd harmonics of 3.64×10^5 Hz. The solid lines are fitted curves (see text)

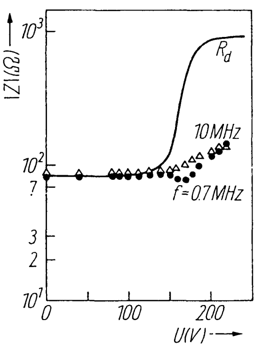


Fig. 3. The absolute value of the ac impedance Z at 0.7 and 10 MHz, and the differential resistance R_d, respectively, as a function of the applied voltage U for a CdSe sample

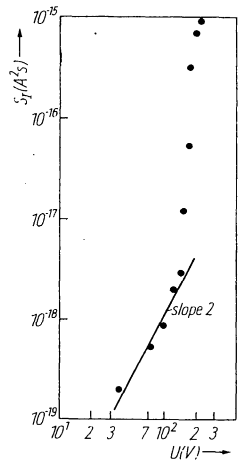
The off-axis angle of maximum amplification was found to be 18°. Theoretically the off-axis angle of maximum amplification increases with increasing voltage until it saturates at 30°, because the electromechanical coupling factor in CdSe has a maximum at 30°. In practice, however, acoustic scattering losses at the crystal side faces reduce the saturation value of the off-axis angle somewhat [4]. As a consequence of the existence of an angular distribution of amplified off-axis waves the resonances occur-ring in Fig. 2 are broader than the theoretical predictions; in the theory a delta-function off-axis distribution was assumed.

According to our potential-trough model the ac impedance apart from the resonances can be described by a smooth function, showing a plateau at high frequencies and two roll-offs, a positive and a negative one, at low frequencies. The solid lines in Fig. 2 represent fitted curves according to the theory. It should be noted that especially at low frequencies the choice of the roll-off frequencies is arbitrary due to a lack of experimental data. The pulse length of 40 μs sets a fundamental low-frequency limit for our measurements. An interesting feature is that, for example, at 0.7 MHz the value of $|Z|$ at 168 V is smaller than the ohmic value R. This effect is even more clear in Fig. 3, where we plotted $|Z|$ at 10 MHz and at 0.7 MHz versus the applied voltage U. The solid line represents the differential resistance R_d as obtained from the I–U characteristic.

4. Current Noise

Fig. 4 shows the spectral current-noise intensity S_I at 3 MHz plotted versus the applied voltage U. The bandwidth was 0.3 MHz. At low voltages ($U < 140$ V) S_I varies approximately proportional to U^2, in accordance with previously published current-noise data on CdS [5]. This noise can be associated with generation–recombination noise. At higher voltages ($U > 140$ V) the sample becomes electro-acoustically active resulting in a strong increase of S_I. Note that the threshold voltage defined by the onset of electro-acoustic current noise $\big(\approx (140 \pm 10)$ V$\big)$ approximately coincides with the onset voltage of current saturation (cf. Fig. 1). Using the threshold voltage (140 V), the contact spacing (1.88×10^{-3} m) and the phase velocity of transverse on-axis waves [9] (1.52×10^3 ms^{-1}) we found the electron drift mobility in our sample to be 2.0×10^{-2} m^2 V^{-1} s^{-1}. The electron Hall mobility in CdSe at room temperature is usually reported to be around 6×10^{-2} m^2 V^{-1} s^{-1} [10]. The low value for the electron mobility found by us could be due to the trapping of free carriers in bound electron states in the forbidden energy gap [4, 11]. Some authors [12], however, reported even Hall mobility values in CdSe ranging from 7.9×10^{-2} m^2 V^{-1} s^{-1} down to $0.5 \times$ $\times$ 10^{-2} m^2 V^{-1} s^{-1}.

Fig. 5 shows current-noise spectra at 168 and at 210 V, respectively. According to the theory [6] the current-noise spectra apart from transit-time resonances consist of two single Lorentzian spectra. The solid lines in Fig. 5 correspond to hand-fitted double Lorentzian spectra; the separate contributions of the single Lorentzians are represented by the dashed lines. The determination of the roll-off frequencies of the-low-frequency Lorentzians is quite inaccurate due to a lack of experimental data and to



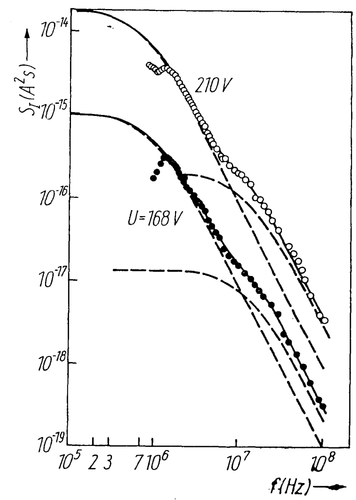


Fig. 4

Fig. 5

Fig. 4. The spectral current-noise intensity S_I at 3 MHz versus the applied voltage U for a CdSe sample. The solid line has slope 2

Fig.5 . Current-noise spectra for a CdSe sample at two different applied voltages. The solid lines are fitted double Lorentzians (theory). The separate contributions of the single Lorentzians to the solid lines are indicated by dashed lines

the occurrence of some small structure. The spectrum at 210 V shows a small local minimum at a frequency (1.1 MHz) where a local maximum occurs in the ac impedance (cf. Fig. 2). This effect was observed before in CdS [4, 5].

5. Conclusion

From the experimental results reported in this paper we conclude that the characteristics of electro-acoustic current saturation, electro-acoustic current noise, and electro-acoustic effects in the ac impedance in CdSe are similar to those in CdS. In addition, the experimental data for CdSe presented here provide a further confirmation of the applicability of the potential-trough model as published previously [6].

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(Received September 17, 1982)