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XI-7. Current Saturation and Instabilities in CdS Crystals

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Current saturation and instabilities associated with phonon amplification were investigated in CdS. Some of the experimental results on current saturation cannot be interpreted by the classical theory but by the quantum theory. The wave number of relevant phonons to current saturation is $10^4 \sim 10^5 \mathrm{cm}^{-1}$. When the minima of oscillating current vs. voltage exhibit negative resistance, high field domains are nucleated and transit through the crystal. The oscillation waveforms of current are closely related to the properties of domains; for example, spike waveforms for dipole domains in dark conductive crystals and sinusoidal waveforms for accumulation layers in photoconductive ones.

§ 1. Current Saturation

The threshold field for current saturation and the buildup time of acoustoelectric current were measured in photoconductive CdS at the various conditions of conductivity, applied field, temperature and crystal dimensions.[1] The experimental results of buildup time are shown in Fig. 1. as a function of conductivity for the various applied fields (ohmic drift velocity) where the drift field was applied perpendicular to c-axis and conductivity was controlled by illuminating the crystal with an incandescent lamp. These results were compared with the classical and the quantum theory. The field dependence of buildup time seems to support the quantum theory. On the other hand, the buildup time calculated by the classical theory[2] under the condition of maximum ultrasonic gain ($\omega^2=\omega_C\omega_D$) increases in a certain region of conductivity with increasing applied field on the contrary to our experimental results. By comparing with the Yamashita-Nakamura theory,[3] the wave number of active phonons was estimated as follows:

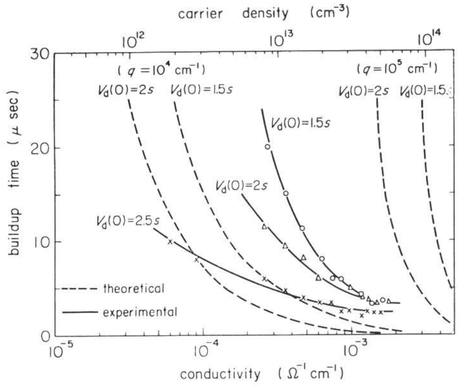


Fig. 1. Buildup time of acoustoelectric current as a function of conductivity in photoconductive CdS, and the estimation of the wave number of relevant phonons by eq. (1).

According to their theory the gain factor γ_q of phonons with wave number q is given by

$$\gamma_q=\frac{VC_q^{\,2}}{2\pi}\left(\frac{m^*}{\hbar^2}\right)^2 f_0(\varepsilon_q)\{v_d(t)\cos\theta-s_q^{\,*}\} \qquad (1)$$

per unit time; where $f_0(\varepsilon_q)$, $v_d(t)$ and $s_q^{\,*}$ are distribution function of electrons, electron drift velocity as a function of time t and effective sound velocity respectively, and the other notations are the same as those in ref. 3). For simplicity we assume that buildup time τ_B of the acoustoelectric current is given by $\tau_B=1/\gamma_q$ and that $v_d(t)=v_d(0)$ (ohmic drift velocity). The calculated curves are shown in Fig. 1 for the appropriate phonon wave number q and the electron drift velocity $v_d(0)$ together with the experimental results. The theoretical curves for $q=10^4\sim10^5\,\mathrm{cm}^{-1}$ are in good agreements with the experimental results. Similar estimation was also made about the conductivity dependence of the threshold field for current saturation; E_{th}, by using the relation $E_{\mathrm{th}}=s_q^{\,*}/\mu$ ($\mu=200\,\mathrm{cm}^2/\mathrm{V\,sec}$: drift mobility), resulting in the same values of q; $s_q^{\,*}$ is defined in their theory as

$$s_q^{\,*}=s+1\Big/\left(\frac{VC_q^{\,2}}{2\pi}\right)\left(\frac{m^*}{\hbar^2}\right)^2 f_0(\varepsilon_q)\tau_q\,, \qquad (2)$$

where s and τ_q are shear mode sound velocity (1.75×10^5cm/sec) and relaxation time of phonons.

From these estimations, it is proposed that the wave number of phonons relevant to current saturation is $q=10^4\sim10^5\,\mathrm{cm}^{-1}$. The frequency of microwave emitted from CdS, which Haydl *et al.*[4] and Miya *et al.*[5] have recently observed, is in the range of these estimations.

§ 2. Current Oscillations in Dark Conductive CdS[6]

Spike waveforms of current oscillations, voltage-controlled negative resistance and high field domains of dipole mode were observed in dark conductive CdS with a conductivity of $0.3\,\Omega^{-1}\,\mathrm{cm}^{-1}$. Figure 2 shows *I-V* characteristics, where the drift field was applied perpendicular to *c*-axis. Above the threshold field E_{th}, the current oscillates between I_1 and I_2; that is, the maximum current is on the ohmic line and the minimum exhibits a negative resistance curve. The oscillatory feature of the current waveform shown in Fig. 3 can be divided into two different parts; *i.e.* τ which is sensitive to the applied field and T which is insensitive to the applied field; therefore, the period T_0 is given by $T_0=\tau+T$. The field dependence of τ and T is displayed in Fig. 4 for two samples of different length. The field dependence of τ is quite similar to that of buildup time of phonon flux as has been discussed in previous section for photoconductive CdS. On the other hand the ratio of the sample length L to the time T: L/T is slightly greater than the sound velocity ($v_s=1.75\times10^5$ cm/sec), being independent of the applied field.

Figure 5 shows the field distribution along the direction of electron flow measured by a capacitive probe at the various times when the current oscillates continuously as shown in Fig. 3. When the current starts to decrease, the high field domain of dipole mode is nucleated near the cathode, and at the instant when the current reaches the minimum value exhibiting negative

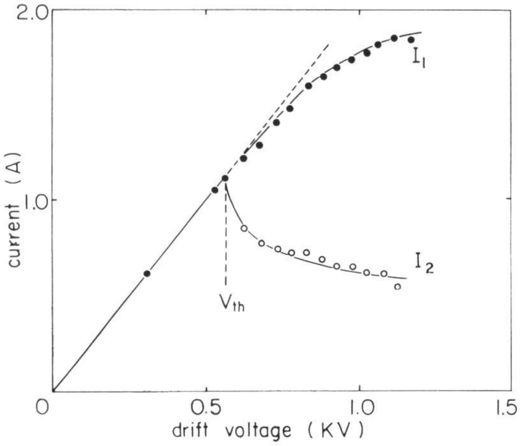


Fig. 2. *I-V* characteristics in dark conductive CdS (sample No. 1). Current oscillates between I_1 and I_2.

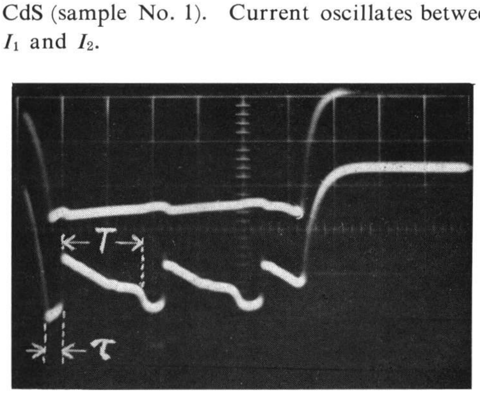


Fig. 3. Waveforms of the applied voltage (upper trace) and the resulting current (lower trace) in dark conductive CdS, and the definition of τ and T (sample No. 1). Applied field: $E=1.3\,E_{\mathrm{th}}$. Horizontal scale: 2 μsec/div.

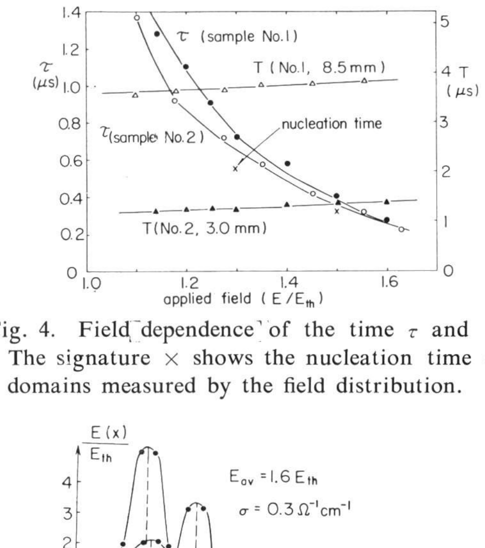


Fig. 4. Field dependence of the time τ and T. The signature $\times$ shows the nucleation time of domains measured by the field distribution.

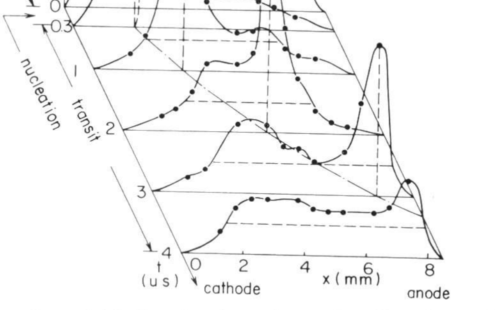
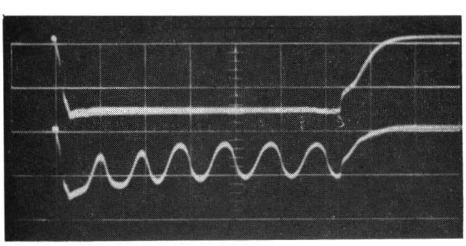


Fig. 5. Field distribution along the direction of electron flow in dark conductive CdS at the various times. High field domain is nucleated near the cathode and travels to the anode.

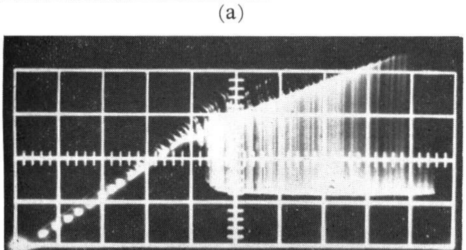
resistance, the high field domain is completely built up; then it travels to the anode requiring the time T stated above. The high field domain leaves the crystal through the anode when the current recovers to the maximum again, and then reappears near the cathode after a time τ, repeating the similar cycles. Accordingly, τ can be considered as the nucleation time of the high field domains which is closely connected with the buildup of phonon flux, and T as the transit time of domains through the crystal. The velocities of domains are 1.8×10^5 cm/sec in sample No. 1 ($L=8.5$ mm) and 2.0×10^5 cm/sec in sample No. 2 ($L=3.0$ mm) in good agreements with the values of L/T.

§ 3. Current Oscillations in Photoconductive CdS

Sinusoidal waveforms of current oscillations, negative resistance and high field domains (accumulation layers) were also observed in photoconductive CdS at the conductivity: $5\times10^{-5}\sim4\times10^{-4}\Omega^{-1}\text{cm}^{-1}$. Figure 6 shows the current waveform and the I-V curve at the conductivity: $1.1\times10^{-4}\Omega^{-1}\text{cm}^{-1}$, where the drift field was applied perpendicular to c-axis and conductivity was controlled in the same way as reported in § 1. Although the minimum values of the current exhibit a negative resistance curve,



(a)



(b)

Fig. 6. (a) Waveforms of the applied voltage (upper trace) and the resulting current (lower trace) in photoconductive CdS at the conductivity: $1.1\times10^{-4}\Omega^{-1}\text{cm}^{-1}$. Horizontal scale: 5 μsec/div. Applied field: $E=1.2\,E_{\text{th}}$. (b) I-V characteristics in photoconductive CdS at the conductivity: $1.1\times10^{-4}\Omega^{-1}\text{cm}^{-1}$. Horizontal scale: 400 V/div. Vertical scale: 2 mA/div.

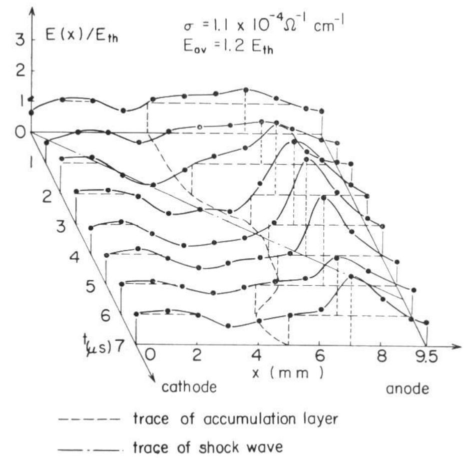


Fig. 7. Field distribution along the direction of electron flow in photoconductive CdS at the conductivity: $1.1\times10^{-4}\Omega^{-1}\text{cm}^{-1}$. High field domain is nucleated near the anode.

the maximum are out of the ohmic line. The period of the oscillation is nearly equal to the constant value: L/v_s (L: sample length, v_s: sound velocity).

The field distribution is shown in Fig. 7 at the various times under the condition of conductivity: $\sigma=1.1\times10^{-4}\Omega^{-1}\text{cm}^{-1}$ and the average field: $E_{av}=1.2\,E_{\text{th}}$. At the instant of the application of the drift field, the high field region exists near the anode.[7] Although the high field domain is nucleated in this region, it does not move on the contrary to the case of dark conductive crystals. On the other hand, the accumulation layer nucleated at the cathode-side edge of the domain migrates along the curve shown by the broken line in Fig. 7. After the field across the domain becomes the highest at the time $t=4\,\mu$sec, it decays gradually until recovering near the initial state at $t=6\,\mu$sec. These oscillatory behaviors of the field across the domain and the accumulation layer seem to result in current oscillations. If it is presumed that the ultrasonic shock wave is generated at the cathode by piezoelectric shock as reported by Sliva and Bray,[8] the time $t=4\,\mu$sec and $t=6\,\mu$sec correspond to the time when the shock wave arrives at the high field domain and that when it leaves the crystal through the anode, respectively.

§ 4. Discussion

When the applied field E exceeds the threshold field for current instabilities, the equation of the current is given by

$$J=n(x, t)e\mu E(x, t)+eD\frac{\partial}{\partial x}n(x, t)+J_{ae}(x, t) \quad (3)$$

as a function of the coordinate x and the time t; where n, e, μ and D are carrier density, electronic charge, drift mobility and diffusion constant respectively. Acoustoelectric current J_{ae} is expressed in terms of Weinreich's relation:[9]

$$J_{ae}=-\frac{\mu}{v_s}\frac{\partial}{\partial t}U(x, t)=-\frac{\mu}{v_s}U(x, t)\gamma(x, t) \quad (4)$$

where $U(x, t)$: acoustic energy density, $\gamma(x, t)$: gain factor of phonons per unit time.

If the field distribution along the direction of electron flow has any spatial fluctuations as shown in Figs. 5 and 7, the absolute value of the acoustoelectric current is greater in high field regions than that in low field regions since the gain factor increases with increasing drift velocity of electrons according to the quantum theory. Under these circumstances the electrons are accumulated at the cathode-side edge of the high field regions and depleted at the anode-side edge through the principle of charge continuity; $\partial J/\partial x=-(\partial\rho/\partial t)$ (ρ: space charge density). Due to such excitation of the space charge layers, the field nonuniformity grows up; which leads to further increase of the acoustoelectric current in high field regions. These processes are repeated until the phonons in the high field regions are completely built up; resulting in the nucleation of the high field domains. In this case, the high field domains are mainly nucleated near the cathode due to the field nonuniformity caused by the injected electrons. The mechanism of domain movement can be interpreted in terms of Ridley's consideration[10] except the locking of the domains for the initial period of the nucleation. Under the condition of constant applied voltage, the field across the low field regions decreases with the nucleation of the high field domains. When the minimum values of the current exhibit a negative resistance curve as shown in Figs. 2 and 6(b), the field across low field regions can be lower than the threshold. In such a case, since the acoustoelectric current flows through the high field domains only, the field distribution recovers to the initial state when the domains leave the crystal through the anode; leading the current to the undamped oscillations. These interpretations are valid in dark conductive crystals.

On the other hand, since the situations are quite complicated in photoconductive crystals, the observed phenomena cannot be interpreted clearly at the stage of this experiment; however, we propose the following interpretation: Since the gain factor of phonons is rather small in this conductivity region, the amplified phonons from thermal background may not be large enough to complete the domain nucleation. If we assume that the ultrasonic shock wave is generated at the cathode,[8] the nucleation of the domains may be completed due to the amplification of the shock wave which just arrives at the high field domains and then the domains may travel to the anode, being accompanied by the shock wave. After the shock wave leaves the crystal through the anode, the nucleation of the domains is started again in high field region and at the same time the shock wave may be excited at the cathode by piezoelectric shock. Therefore, the period of the oscillations may be determined by the transit time of the shock wave through the crystal.

As a result, it is proposed that the nonuniformity of electric field plays an important role to nucleate the high field domains or the accumulation layers in both dark conductive and photoconductive crystals. Okada and Matino[7] have discussed the current oscillations in photoconductive CdS with a high resistivity region near the anode in terms of feedback mechanism between the electric and the acoustic systems.

§ 5. Conclusion

The field dependence of buildup time of the acoustoelectric current cannot be interpreted by the classical theory, but it seems to support the quantum theory. The wave number of the relevant phonons to current saturation is concluded to be in the range of $10^4 \sim 10^5\,\mathrm{cm}^{-1}$.

When the minimum values of the oscillating current exhibit a negative resistance curve, the high field domains are nucleated due to the field nonuniformity and the undamped current oscillations occur in both dark conductive and photoconductive crystals. Spike waveforms of current oscillations in dark conductive crystals arise from the nucleation and the movement of the dipole domains due to the buildup of phonon flux. Sinusoidal waveforms in photoconductive ones may be due to the migration of the accumulation layers or to the nucleation of the high field domains assisted by the ultrasonic shock wave.

References

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DISCUSSION

Yokota, I.: The quadratic term in your expression for $1/\tau$ is much interesting in that it demonstrates the nonlinear character of the mechanism of stopping the phonon buildup, noting that γ is proportional to the phonon density in the stationary state after the phonon is fully built up.

Ishida, A.: The observed phenomena cannot be attributed clearly to the higher-order electron-phonon interaction, because the theoretical formulation is quite complicated and the experimental data are still insufficient. Detail of this experimental data will soon appear in J. Phys. Soc. Japan **21** (1966) No. 10.