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Photoinduced Hall-current measurements in photorefractive sillenites

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Hall currents are excited in the photorefractive sillenite crystals BSO, BGO, and BTO [$Bi_{12}Si(Ge,Ti)O_{20}$] using an externally applied magnetic field and an internal electric field of a space charge grating. We measure Hall mobilities of photoexcited electrons and obtain the values $\mu = (5.5 \pm 1.0)$ cm^2 V^{-1} s^{-1} for BSO and BGO and $\mu = (2.5 \pm 0.5)$ cm^2 V^{-1} s^{-1} for BTO.

I. INTRODUCTION

During the past 30 years photorefractive effects in electro-optic crystals have been intensively studied.[1] Illumination excites charge carriers that migrate in the conduction or valence band and are captured in dark regions. A space charge field builds up and modulates the refractive index via the electro-optic effect. Photorefractive crystals enable many promising applications, e.g., optical data processing, dynamic phase conjugation, and volume holographic storage.[1] Knowledge of the microscopic crystal parameters is necessary for proper modeling of the photorefractive effect and for an optimization of the crystal performance.

Many attempts have been started in order to determine the charge carrier mobility, which is among the most important parameters of the light-induced charge transport. Conventional Hall measurement, the most direct technique, is not appropriate for highly insulating crystals.[2] Data for drift mobilities have been obtained by conventional and holographic time-of-flight techniques or by photoconductivity relaxation measurements, but these data cover a very wide range for each material. The sillenites BSO, BGO, and BTO [$Bi_{12}Si(Ge,Ti)O_{20}$] are of special interest for photorefractive applications because of small response times and large sensitivities for red light.[1] For BSO and BGO drift mobility values from 5×10^{-5} to 1 cm^2 V^{-1} s^{-1} have been reported.[2–7] This scattering of the data is usually attributed to the influence of shallow traps which reduce the averaged velocity of excited carriers. For this reason Hall measurements, in which only moving carriers participate, are of fundamental importance. In this contribution we report on Hall mobility data of BSO, BGO, and BTO obtained by a technique developed for highly insulating photoconductors.

II. EXPERIMENTAL METHODS

In contrast to the conventional Hall techniques our method utilizes the internal space charge field for the excitation of the primary current,[8] instead of an externally applied electric field. The experimental arrangement is illustrated in Fig. 1. For the generation of an interference pattern we use an Ar$^+$ laser beam of wavelength $\lambda = 514$ nm. The light is spatially filtered, expanded, and split into two coherent plane waves of nearly equal intensity (total light intensity 0.2 W cm^{-2}) entering the crystal symmetrically. The spatial frequency of the generated interference pattern is about 6×10^3 cm^{-1}. The light is always polarized perpendicular to the plane of incidence. A sinusoidal phase shift of frequency $\omega_L = 140$ Hz and amplitude 1.0 rad between the coupling beams is produced by an electro-optic modulator. This yields a vibration of the interference pattern and as a consequence an alternating volume current along the grating vector is excited because of the time varying phase shift between free carrier and space charge field distributions.[9] The crystal is contacted with one pair of silver paste electrodes and the generated photocurrent I is measured by a lock-in amplifier (input resistance 100 MΩ; integration time 12.5 ms). For the generation of a magnetic field we use a conventional electromagnet. In order to increase the sensitivity of this technique we modulate the magnetic field induction according to $B(t) = \Delta B(1 + \sin \omega_B t)$ with the frequency $\omega_B = 0.6$ Hz and

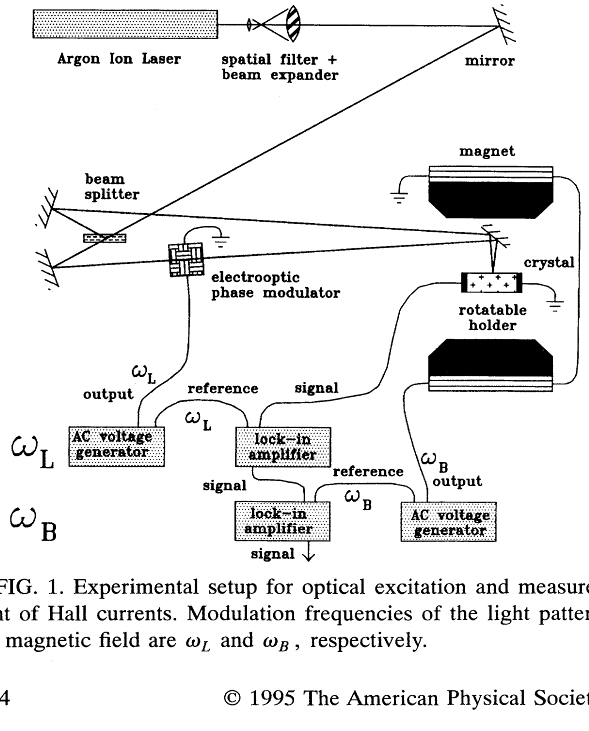

FIG. 1. Experimental setup for optical excitation and measurement of Hall currents. Modulation frequencies of the light pattern and magnetic field are ω_L and ω_B, respectively.

the amplitude ΔB up to 0.2 T. The analog output of the first lock-in amplifier is used as an input signal for a second lock-in amplifier (input resistance 100 MΩ; integration time 30 s) which determines the ω_B component I_H of the signal.

A BSO, three BGO, and a BTO sample are investigated. The dimensions are $2.0\times5.5\times10$ mm^3, $3.7\times7.0\times6.8$ mm^3, and $6.0\times3.3\times4.5$ mm^3 for the BSO, BGO, and BTO samples, respectively. The first dimension corresponds to the direction of light propagation. Input and output surfaces are polished to optical quality.

The Hall mobility measurements are performed as follows: At first we determine the alternating photocurrent I along the space charge field grating vector. Then the crystal is rotated by 90° around the magnetic field direction in order to obtain the optimum suppression of the photocurrent I. Then the magnetic field is switched on and the Hall component of the current I_H is measured by the same pair of electrodes. Under the assumption of monopolar photoconductivity the Hall mobility μ of photocarriers is given by

$$\mu=\frac{1}{\Delta B}\frac{I_H}{I} . \tag{1}$$

This technique has several evident advantages as compared with the conventional Hall technique. (1) Conventional Hall measurements require point electrodes in order to avoid any influence of the electrodes on the main current. In the technique presented here the main current is generated in the whole volume and thus full size electrodes can be used for measurements of the Hall currents. The signal increases proportional to the electrode area and therefore much smaller mobilities can be detected. (2) The usual problem of nonequipotential position of the measuring electrodes can be easily solved by an appropriate rotation of the crystal around the magnetic field direction. (3) In order to avoid screening effects, conventional Hall measurements are usually carried out with externally applied alternating fields.[10] As a consequence pronounced electromagnetic noise appears. Because of the optical excitation of the primary current this problem does not arise for our technique.

To obtain the Hall signal with high accuracy some details of the experimental realization require special care. (1) It is necessary to use a rotatable crystal holder free of any ferromagnetic component. Otherwise the magnetic force can tilt the crystal and generate a signal modulated by the magnetic field. (2) Homogeneous illumination of the sample is important in order to ensure equal electrical resistivity of the sample for both crystal orientations. (3) The frequency of light modulation should be high enough to provide by the crystal capacity a short-circuited regime for the primary current.

III. EXPERIMENTAL RESULTS

The initial photocurrent signal measured by the first lock-in (input resistance 100 MΩ; capacity of crystal, cable and lock-in amplifier 150 pF) ranges for different crystals from 0.2 up to 0.5 V. Using the described arrangement, we obtain a pronounced Hall current with a signal to noise ratio up to 10:1. From the sign of the Hall current electrons are determined as the dominant charge carriers in all samples under investigation, in agreement with results of holographic measurements.[11] A typical dependence of the Hall signal on the modulation amplitude ΔB is shown in Fig. 2. Obviously the expected relation $I_H \propto \Delta B$ is fulfilled. For BSO and BGO the measured ratio between Hall current and primary current I_H/I is about 5.5×10^{-5} for ΔB = 0.1 T and for BTO this ratio is about 2.5×10^{-5}. According to Eq. (1) these ratios yield for BSO and BGO the Hall mobility μ = (5.5 ± 1.0) cm^2 V^{-1} s^{-1} and for BTO μ = (2.5 ± 0.5) cm^2 V^{-1} s^{-1}. The error statements relate to the reproducibility of the results after replacing the crystal and complete adjustment of the setup.

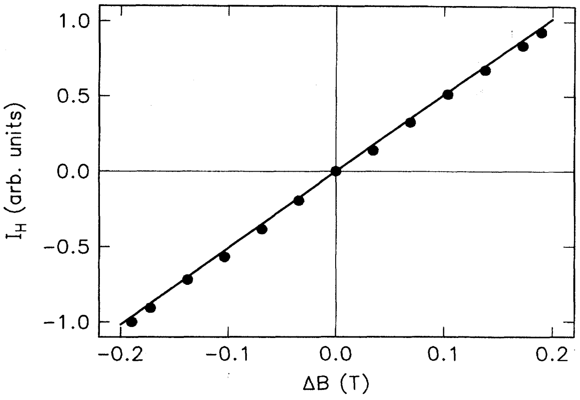

FIG. 2. Hall signal I_H vs modulation amplitude ΔB of magnetic induction $B(t)=\Delta B(1+\sin\omega_B t)$ for a BGO sample. A change of the sign of the magnetic field provides a change of the sign of the Hall signal. The symbols represent measured data and the solid line is a linear fit.

IV. DISCUSSION

The Hall mobility values determined by our measurements are at least one order of magnitude larger than the drift mobilities measured by various techniques.[2–7] The differences are much larger than the experimental errors. Most probably the reason is that the excited charge carriers spend a relatively long time in shallow traps[2] and as a result the averaged velocity of excited carriers is reduced. Furthermore, drift mobilities can vary from sample to sample because of different types or different concentrations of shallow centers. Additionally, illumination may saturate shallow centers and provide an intensity dependence for the drift mobility.

Our experimental data for BSO are in fairly good agreement with the intrinsic mobility μ = 3.2 cm^2 V^{-1} s^{-1} determined by Le Saux and Brun[12] from photoconductivity measurements, where charge carriers were excited by laser pulses. Under the assumption of a two-acceptor model these authors estimate also for the drift mobility μ = 0.5 cm^2 V^{-1} s^{-1} which is in satisfactory agreement with drift mobility data obtained by the holographic time-of-flight technique.[3,5,6]

V. CONCLUSIONS

We have developed a technique which enables Hall mobility measurements for high resistivity photoconductive crystals. Application of this technique to photorefractive sillenites yields the Hall mobility $\mu = (5.5 \pm 1.0)$ $\mathrm{cm^2\,V^{-1}\,s^{-1}}$ for BSO and BGO and $\mu = (2.5 \pm 0.5)$ $\mathrm{cm^2\,V^{-1}\,s^{-1}}$ for BTO. Comparison of these results with drift mobility data available from literature indicates that the photoexcited electrons spend less than 1/10 of time in the conduction band.

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