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The features of phonon component of linear dichroism in uniaxially strained silicon crystals

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Abstract. Linear dichroism induced by uniaxial compression strain in semiconductor silicon samples was studied with modulation spectroscopy technique using modulation of electromagnetic radiation polarization. We obtained a spectral characteristic of the difference between transmissions for polarizations parallel to the different axes of the optical indicatrix of the sample studied in the edge absorption region. A fine structure of characteristics was found in which one can observe event of acoustic phonons in the interband transitions. From the results of measurements of the total and difference transmission characteristics we calculated spectral dependence of linear dichroism. It has singularities related to the indirect interband transitions.

Keywords: polarization, anisotropy, dichroism, modulation, silicon, phonon.

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1. Introduction

Silicon crystals belong to the cubic symmetry system and are isotropic. Therefore dichroism can appear in them only due to some oriented external action (say, uniaxial compression) that lowers crystal symmetry. This effect is one of the basic polarization effects in anisotropic crystals. It consists in distinction of absorption coefficients of linearly polarized radiation for the cases when the electric component of electromagnetic wave is oriented in parallel to the crystal optical axis or at a normal to it.

Detection and observation of the above effect are based on the fact that, in the wavelength range of partial light absorption, the intensity of light after passing the sample studied varies when the radiation polarization plane turns relative to the sample axes. At that the difference between the transmission coefficients is determined by (i) the sample thickness, (ii) difference between the complex refractive indices for waves polarized in parallel to the different axes of optical indicatrix, and (iii) dispersion of these indices (which, generally, may differ from that of refractive index of isotropic crystal). In this connection investigation of linear dichroism seems to have information ability concerning the crystal band structure, as well as mechanisms for radiation absorption and

their peculiarities. This was shown, for instance, in [1, 2] where some features related to phonon participation in the indirect optical transitions were found in the cited electroabsorption spectra of silicon crystals.

Linear dichroism induced by a uniaxial strain in silicon crystal still remains unexplored. A possible reason for this may be the fact that, due to big values of silicon elastic constants, variation of its bandgap under uniaxial strain is too small for observation of linear dichroism with traditional techniques. But if one applies modulation spectroscopy for registration of this effect, one could expect that some its features could be found which manifest themselves in a differential technique only. At that there are two versions of the experimental procedure. In one of them (based on piezomodulation [3]) the sample is exposed to linearly polarized light of constant intensity, while variation of absorption is realized by uniaxial strain varying with time. In another case strain remains unchanged, while radiation polarization is modulated. This means that the sample is illuminated with light (of constant intensity) that is incident completely perpendicularly to the sample surface, while the electric component \vec{E} of the linearly polarized wave alternately varies its orientation relative to the crystal optical axis.

Due to some reasons, application of the second version in modulation spectroscopy is less common. However (as was demonstrated in practice [4]), it may have higher information ability, and the results obtained with it may be interpreted more reliably. At that one should take into account that in silicon (due to its indirect band spectrum) interband light absorption involves phonons over a wide fundamental absorption range. Thus investigation of phonon contribution into linear dichroism in the edge absorption range of silicon with modulation-polarization spectroscopy is the objective of this work.

2. Experimental results

The essence of the technique used is realized in the optical system schematically presented in Fig. 1. A sample (experiencing uniaxial compression of a fixed value) is illuminated with polarized light whose polarization varies with time. The azimuth of the electric component \vec{E} of linearly polarized wave alternately (periodically) becomes oriented in parallel and at a normal to the crystal optical axis. In this case, due to dependence of the light absorption coefficient on orientation of \vec{E} , a difference $\Delta T = [T_{\perp}(h\nu) - T_{\parallel}(h\nu)]$ of transmission values appears. It produces an alternating signal in a measuring device that registers the intensity of radiation passed through the sample. Thus, at partial light absorption in the sample, each of the spectral transmission dependencies $[T_{\perp}(h\nu)$ and $T_{\parallel}(h\nu)]$ of transmitted light carries its own information on the absorption features stemming from the corresponding dependencies of absorption coefficients on photon energy. So, after subtracting one of these dependencies from another, the difference contains the result that is inherent in one characteristic only and is absent in another.

The samples for measurements were made as plates of weakly doped *p*-Si (resistivity of 200 Ω -cm at 300 K). After each measurement the sample thickness (along the direction of light propagation) was decreased by lapping; it took on the values 3, 2, 1 and 0.5 mm. The sample

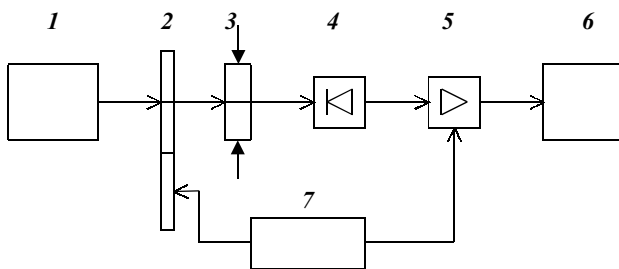


Fig. 1. Schematic presentation of the optical system for linear dichroism measurements with the polarization modulation technique: 1 – source of circularly polarized monochromatic radiation (an incandescent lamp, monochromator, linear polarizer, achromatic phase plate); 2 – photoelastic polarization modulator; 3 – sample; 4 – photodetector (a germanium photodiode); 5 – lock-in amplifier; 6 – two-coordinate plotter; 7 – harmonic oscillator.

orientations were such that strain direction coincided with one of the basic crystallographic directions ([100], [110] or [111]); the illuminated surface always was the (110) plane. The samples were treated according to the standard procedure. It provided obtaining flat, parallel and specular surfaces. They were strained using a special system which enabled one to measure deforming forces with a special device. The optical system for polarization-modulation spectroscopy is schematically presented in Fig. 1. It has a monochromator MDR-4 (serving as source of circularly polarized radiation of changeable wavelength) with a halogen tube at its inlet, linear polarizer and achromatic quarter-wave phase plate.

The effect to be measured (it is usually registered with a selective amplifier) should be due to variation of light polarization rather than intensity. Therefore light intensity has to be constant (with a sufficient degree of accuracy) at polarization modulation. This is achieved by using a radiation polarization modulator based on the photoelastic effect [5]. Such modulator is made as a dynamic phase plate. Alternating anisotropy of its dielectric properties is made by a standing compression-stretching wave coming from an attached cavity made of crystalline quartz. By varying the plate size, one places the wave nodes at plate ends, while the antinode (i.e., the highest deforming force) is at the plate center (Fig. 2a). The phase delay is $\delta = \delta_0 \sin \omega t$ where δ_0 is the quarter-wave delay (set by the quartz cavity supply voltage) and

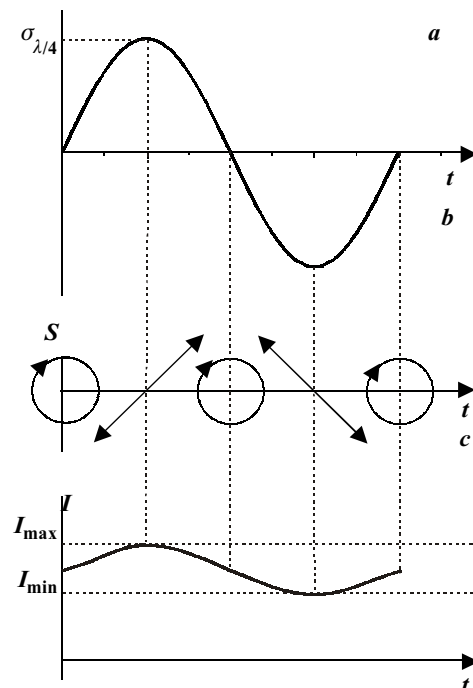


Fig. 2. Illustration of polarization modulation and results of its action. Time dependencies of: a – stress at the central part of the phase plate (where the standing compression-stretching wave produces phase delay of $\lambda/4$); b – polarization of radiation leaving the polarization modulator, at $t = 0, T/4, T/2, 3T/4, T$ (T is the vibration period); c – the intensities of radiation passed through the sample ($I_{\max} - I_{\min}$ is the registered signal).

ω is the modulator eigenfrequency. At those moments when the phase delay becomes $\delta_0 = \pi/4$, the circular polarization is transformed by the modulator into linear one. During a period radiation twice becomes linearly polarized, with orthogonal azimuths of the electric component of the wave (Fig. 2b).

Polarization is related to the azimuthal position of modulator in a certain manner. Therefore one can set the electric components in parallel to the crystal optical indicatrix axes by rotating modulator about the optical axis. In this case, due to linear dichroism, the sample takes on the properties of a linear polarization analyzer. So the intensity of radiation passed through the sample varies with a frequency ω (Fig. 2c). The intensity was transduced into electric signal with a germanium photodiode. Then the signal obtained was amplified with a lock-in nanovoltmeter and recorded by a two-coordinate plotter. The measurements were performed at room temperature; the light intensity was at the level of 10^{15} photons/cm²·s.

3. Discussion

When discussing the results of measurements, one should bear in mind that in silicon crystals radiative interband transitions occur with phonon absorption (emission) in the energy range from the bandgap up to the closest vertical transition at $h\nu = 3$ eV. Recall that uniaxial strain of silicon crystal along the crystallographic direction [111] lifts degeneracy of the valence bands, while those along the other two basic crystallographic directions lift degeneracy of the conduction band as well. As a result, instead of the only possible (in the isotropic case) transition, we have now four transitions differing in their energies and selection rules relative to the polarization states.

The valence band extremum that appeared due to strain involves mixed V_{\pm} -states of heavy and light holes. The conditions for transitions from them depend on the polarization state. For instance, the transition from the V_{+} -state is allowed for two polarizations, while that from the V_{-} -state is forbidden for polarization parallel to the strain axis [6]. In consequence of this, the corresponding absorption coefficients are different, thus resulting in a non-zero difference $T_{\perp} - T_{\parallel}$ between the transmission coefficients. The spectral dependencies of this difference (that are the transmission difference characteristics of a [100]-oriented silicon sample) are shown in Fig. 3 for three stress values. In the first approximation they resemble a derivative of the typical transmission characteristic of an unstrained sample.

Indeed, when the wavelength of light passing through a sample is varied, then the maximal slope of the transmission characteristic occurs at $\alpha d \approx 1$ (here α and d are the absorption coefficient and sample thickness, respectively). In anisotropic case this characteristic splits into two (for orthogonal polarizations). It seems natural that the difference between their ordinates (which is virtually the result presented in Fig. 1) will be maximal in the region where the characteristic slope is the biggest.

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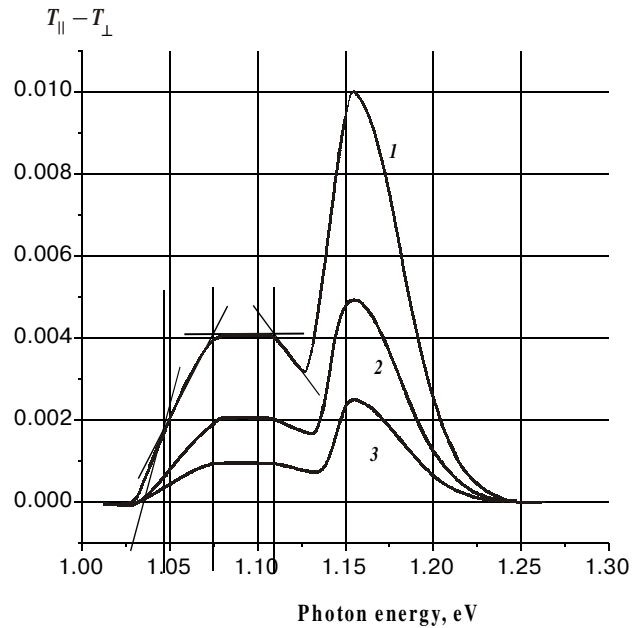


Fig. 3. The difference of transmission coefficients ($T_{\perp} - T_{\parallel}$) as function of the energy of photons passed through the sample 1 mm thick at different stress values: 1 – 4; 2 – 2; 3 – 1 kbar.

However, contrary to the ordinary derivative, the dependencies shown in Fig. 3 have fine structure. It manifests itself, first of all, in presence of two extrema (at least for the samples strained along the crystallographic axis [100]). One should note that the extrema positions relative to the x -axis do not depend on the deforming force value (i.e., are not related to the splitting of either valence or conduction band). Moreover, one can see that the curves in Fig. 3 consist of piecewise-linear sections joined smoothly to each other.

Extension of the linear sections until they consecutively intersect each other enables one to obtain information concerning some regularities in their positions on the energy axis. Thus the section located between the 1.048 and 1.075 eV energy values is (to within meV) twice as big as the exciton binding energy cited in [7]. The next section of the spectral characteristic (preceding the above) has different slope, but its length along the energy axis is comparable to the same binding energy value. It should be noted that such interpretation of the above characteristic agrees with the results of measurements of electroabsorption in silicon samples in the same energy range [2]. And, finally, the third linear section located between the 1.075 and 1.109 eV energy values correlates well with twice the energy of the TA (transverse acoustic) phonon given in [8].

An analysis of the spectral characteristics presented in Fig. 3 is illustrated by processing of curve 1 only. However, similar consideration of the remaining curves gives the same energy values for the intersection points. Further still, the noted features of linear section position remain at varying the sample thickness. One can see this from Fig. 4. It shows evolution of the spectral character-

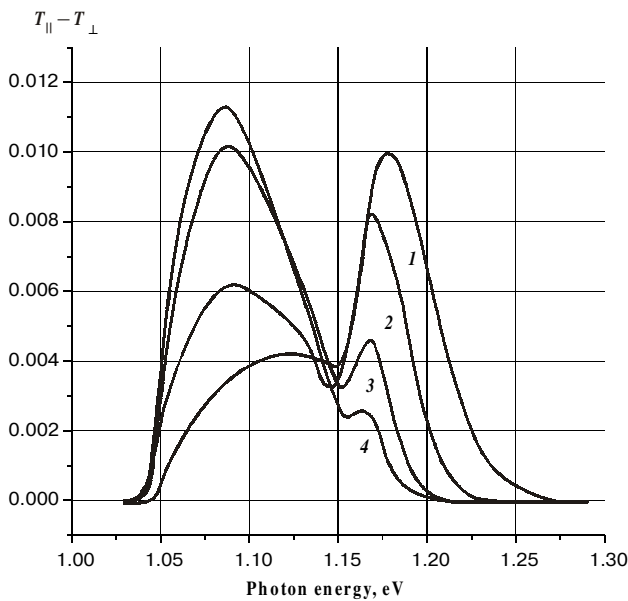


Fig. 4. The spectral dependencies of transmission variation for the silicon samples strained with the same deforming force ($\sigma = 0.7$ kbar) but differing in their thicknesses d along the direction of light propagation. d (mm) = 1 – 0.5; 2 – 1; 3 – 2; 4 – 2.8.

istics of induced dichroism in silicon samples at varying their thickness along the direction of light propagation. Due to the condition $\alpha d \approx 1$, the edge of the transmission characteristic shifts as sample thickness decreases. Therefore shifting of the region where the slope of this characteristic is the biggest results in a change in the ratio between the curve peaks. An analysis performed by us shows, however, that positions of both the extrema and phonon singularities remain fixed relative to the energy scale.

One should note some features of the spectral characteristics related to sample orientation with respect to the crystallographic axes. To illustrate, in the samples strained along the [110] axis the differential transmission characteristic also involves two bands (although less pronounced). This correlates with the fact that, at the above orientation of the sample, the conduction band splitting is below that at [100]. And, finally, at orientation [111] the differential transmission characteristic consists (as one would expect) of the only band which, as in the previous case, involves well-defined linear sections.

It is possible to get spectral dependence of the difference between the absorption coefficients for orthogonal polarizations from the integral transmission characteristic and that obtained with the polarization modulation technique. From the known interrelation between the transmission and absorption coefficients (T and a) one can obtain the expression $\Delta\alpha = \alpha_{\parallel} - \alpha_{\perp} = \ln[1 + (\Delta T/T)]/d$ that describes the spectral characteristic of the difference of transmission coefficients. This calculated characteristic is presented in Fig. 5, along with the dependence (taken from [9]) of the reduced absorption coefficient on the photon energy (at the semi-root-square scale). From com-

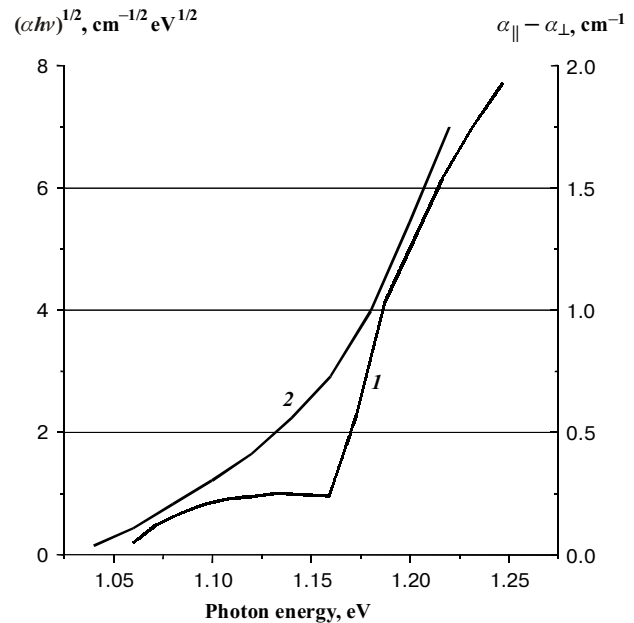


Fig. 5. The spectral dependencies of the increases of absorption coefficient (curve 1 calculated from the plot in Fig. 1 at $\sigma = 4$ kbar) and reduced absorption coefficient in an isotropic crystal (curve 2 taken from [9]).

parison between these curves one can conclude that the effect of phonons with energies of about 50 meV is more pronounced in $\Delta\alpha$ than when α is measured in unpolarized light.

Another conclusion (of the same importance) is that the polarization-modulation technique for measurements of linear dichroism enables one to find additional (as compared to the potentialities of other techniques) electron-phonon interaction. This is evidenced by Fig. 5 where one can see linear sections of the spectral characteristic $\Delta\alpha$ which are comparable to the energy of TA-phonons. The phonon nature of these linear sections is also evidenced by additional experiments where $\Delta\alpha$ was measured at $T = 78$ K for the same samples, as well as those made of heavily doped silicon. In both cases the predominant charge carrier scattering mechanism was that by impurities. This fact excludes phonon manifestation in both $\Delta\alpha$ and ΔT .

One can see from comparison between the curves in Fig. 5 that the role of optical phonons in transitions is more pronounced for polarized radiation. Thus curve 1 has the same break (concurring with the bandgap) as for the unstrained sample. However, the intensities of transitions with phonon absorption and emission are quite different. But in both cases the $\Delta\alpha$ curve illustrates (by its linear sections) the concurrent process involving acoustic phonons.

One can understand the origin of the linear sections of the $\Delta\alpha = F(h\nu)$ curve if one assumes that a linear function also enters the power dependence describing the spectral transmission characteristic for one of polarizations only. The nature of this linear function may be related to

the fact that low-energy phonons are involved. At any rate, this assumption agrees with the aforementioned distinction in selection rules for transitions from V_{\pm} to the conduction band. Anyhow the same power dependencies entering the transmission curves T_{\perp} and T_{\parallel} cancel each other when subtracting these curves in the polarization modulation technique. So it seems that the result for linear dichroism in a uniaxially strained crystal obtained with the modulation procedure stems from the fact that radiation transitions with polarization parallel to the strain axis are forbidden.

4. Conclusions

Our results indicate, first of all, at high sensitivity of the polarization modulation technique to anisotropy of dielectric properties of the crystals studied. Such a conclusion correlates with the general characteristic of all the other differential spectroscopy techniques. The above technique, however, has (as any of the other ones) its own specific character that determines its applications. One of such applications might be detection of anisotropy induced by external physical actions and investigation of its spectral, amplitude and other characteristics. Besides, the presented technique for study of linear dichroism, as well as the results obtained with it, gives grounds for application of polarization-modulation spectroscopy in a wider energy range than that used in this work. For this one should provide (by varying sample thickness) semitransparency, with allowance made for absorption coefficient growth as photon energy increases. At that one could apply tensile (rather than compression – it is not critical) strain for too thin samples. And usage of samples with different crystallographic orientations will make it possible to identify the transition character as concerning presence of singularities in other sections of the Brillouin zone too.

The final remark deals with practical applications of the results obtained. Along with the aforementioned possibility for testing the band structure singularities, the effect of linear dichroism, combined with the presented procedure, may give grounds for diagnostics of semiconductor crystals and devices as concerning presence of inhomogeneities and intrinsic stresses related to them. The experiments proved that standard equipment enables one to detect for sure minimal stress of about 1 kg/cm^2 . At that one should bear in mind that this value relates to the peak of the spectral characteristic of dichroism.

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