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Sample illumination facility for slow positron beam studies and its application to the photoionization cross-section of the DX center in $Al_xGa_{1-x}As$

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Abstract

We have built a sample illumination facility for slow positron beam studies. It enables the illumination of the sample with monochromatic light in visible and near-IR wavelength range with the maximum photon flux of 10^{13}–10^{15} s^{-1} cm^{-2}. Light is guided from the monochromator into the vacuum chamber by an optical fibre bundle and focused onto the sample with a mirror and a lens. We have applied the new illumination facility in studying the photoionization cross-section of the DX center in AlGaAs. The measurements were done using photon energies in the range of 1.0–1.6 eV and the cross-sections were calculated from the behaviour of the positron annihilation parameters as a function of the photon fluence. The resulting photoionization cross-sections were found to coincide well with the results from the photo-capacitance measurements.

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1. Introduction

By illuminating a semiconductor with photons of suitable wavelength, it is possible to induce optical excitations in defects. The charge state of the defect may change in these excitations and this change can be detected by the positron annihilation spectroscopy. An interesting example is the DX center which can be observed in $Al_xGa_{1-x}As$ when $x > 0.22$. The DX center is a localised donor related defect, which captures electrons into a deep state thus limiting the charge carrier concentration in n-type $Al_xGa_{1-x}As$ [1]. Electrons can be optically ionised from the deep state. At low temperatures, this leads to persistent photoconductivity due to an energy barrier related to the capture of a free electron. The properties of the DX center are most commonly explained by a large lattice relaxation taking place around the impurity atom [2]. This relaxation leads to a vacancy-like open volume in defect site. If the DX center is ionised optically or thermally, the vacancy defect disappears. The vacancy defect related to the DX center can be detected by positron annihilation spectroscopy [3].

The aim of this study was to build a sample illumination facility to be assembled to the target

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chamber of HUT slow positron beam. The intended illuminating range was in the visible and the near-IR part of the spectrum. The sample illumination facility was applied into the study of the photoionization cross-section of the DX center in $Al_xGa_{1-x}As$. In this paper, we briefly describe the construction of the sample illumination facility and then we give the experimental details and the results of the photoionization cross-section study.

2. Implementation

As a light source we use a monochromator (ARC Spectra Pro 275) equipped with a 250-W tungsten halogen lamp. Light is guided from the monochromator onto the sample by an optical fibre bundle consisting of VIS-IR grade quartz fibres ($\phi = 0.13$ mm). The fibre bundle offers flexibility to monochromator positioning and the monochromator, which contains magnetic parts, can easily be situated far away from the beam line. The bundle is divided into two branches: One branch is used for illumination and the other, which carries $\sim 10\%$ of the total intensity, for the flux control. The attenuation in intensity due to the fibre bundle is $\sim 65\%$, caused mainly by the reflections at the fibre ends and the limited packing density of the bundle.

Fig. 1 shows a schematic overview of the illumination facility installed in the target chamber of HUT slow positron beam. Inside the vacuum chamber, the fibre bundle is placed inside a steel tube ($\phi = 15$ mm). The tube is welded to a simple manipulator to enable rough position control of the tube end. A sapphire window closes the other end of the tube. The light entering from the sapphire window is turned onto the sample surface by a front surface mirror. The need for this mirror rises up purely from the difficult geometry of our target chamber.

If the illumination feedthrough is assembled too close to the sample, the backscattered positrons hitting the steel tube will corrupt the annihilation spectrum. To reduce the effect of the backscattered positrons, the distance between the sample and the mirror was set to ~ 50 mm (mirror ~ 20 mm above the beamline). The long distance between the sample and the mirror causes reduction in the intensity. This was compensated by installing a simple focusing lens ($f = 18$ mm) between the sapphire window and the mirror. With this lens the intensity was doubled.

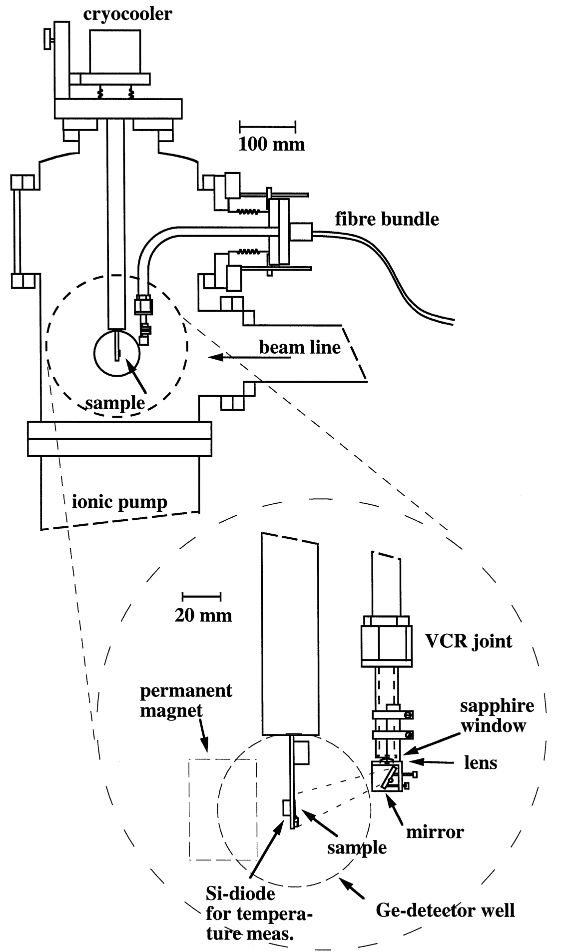

Fig. 1. The schematic overview on the sample illumination facility installed in the target chamber of HUT slow positron beam.

3. Flux control

A LabView based program running on a PC controls the measurement routines. The program controls the illumination parameters (the wavelength and the flux), the sample temperature, the MCA and the positron implantation energy. The accelerating voltage supply is optically isolated from the controlling computer in order to prevent damage in case of an HV breakdown. The illumination flux is adjusted by controlling the lamp power. The feedback for accurate control is provided by a photodetector, which measures the intensity from the reference branch of the fibre bundle. The calibration between the output of the reference detector and the real flux entering the sample surface is done by positioning a photodetector at the sample position. The achieved flux on the sample surface is 10^{13}–10^{15} s^{-1} cm^{-2} in the wavelength range of 450–1800 nm. The smaller maximum flux at shorter wavelengths results from the emission spectrum of the halogen lamp. A different light source, e.g. an arc lamp, is needed for reaching short wavelengths down to 350 nm with reasonable flux values.

The accurate estimation of the light intensity at certain depth inside the sample is not straightforward. In the wavelength range where the sample material is transparent, internal reflections from surfaces and from the sample holder behind the sample increase the total intensity. Especially if the sample consists of multiple layers of different materials, the estimation of the intensity becomes very complicated. An additional source of inaccuracy in intensity measurement is also the inhomogeneous intensity distribution over the sample surface. The intensity distribution across the spot diameter is almost Gaussian shaped and with the current set-up, the intensity varies by almost 30% inside a 10-mm spot.

4. Application: the study of the photoionization cross-section of the DX center in AlGaAs

4.1. Experimental

The studied sample was a 2-μm thick Si-doped $Al_{0.29}Ga_{0.71}As$ overlayer grown on SI GaAs substrate. Between the $Al_{0.29}Ga_{0.71}As$ layer and the substrate was a ~230-nm thick superlattice structure, which consisted of ten pairs of alternating GaAs and AlGaAs layers, each with the thickness of ten monolayers. On top of the $Al_{0.29}Ga_{0.71}As$ layer, there was a thin 5-nm GaAs layer. In earlier positron annihilation measurements, this sample was found to contain vacancy-like defects which were identified as DX centers [3]. The concentration of the DX centers was estimated to be $\sim 1\times10^{18}$ cm^{-3}.

The measurements were done using a slow positron beam with the positron implantation energy of 15 keV, which gives the mean penetration depth of ~0.6 μm in AlGaAs. The annihilation spectrum was recorded using a Ge-detector and the Doppler broadening of the 511 keV annihilation line is described using the conventional core annihilation parameter W [4]. Because of the missing positive ion core in vacancy site, the positrons can be trapped at vacancies. The positron trapping at vacancies is seen as a decreasing W parameter as the probability of the trapped positron to annihilate with the core electrons is smaller.

The measurements were started by cooling the sample down to 25 K in the dark. The annihilation parameters recorded at this state correspond to positron trapping at DX center related vacancies. When the sample is illuminated with the light of suitable wavelength, the DX centers become ionized and the vacancy signal disappears. If all DX centers are ionized, the annihilation parameters correspond to the annihilation in perfect bulk lattice. The behaviour of the annihilation parameters as a function of illumination fluence was recorded by alternating the illumination and measurement periods in short cycles until the annihilation parameters were seen to saturate to the bulk level. The illumination time in one cycle was 400–800 s and the flux 10^{14}–10^{15} s^{-1} cm^{-2}, depending on the photon energy.

The measurements were done in the photon energy range of 1.1–1.6 eV. The bandwidth of monochromatic light corresponded to 0.03 eV in energy scale. The intensity of light inside the sample was estimated by modelling the sample by a 0.5-mm thick slab of GaAs. In energy range where GaAs is highly absorbing ($E_{ph} > 1.4$ eV) the only correction to the flux value was the reflection from the outer surface (~30%). In transparent region ($E_{ph} < 1.3$ eV), we added the effects from internal reflections by assuming the sample holder (copper) behind the sample to be fully reflective.

Between the measurements with different photon energies, the positron trapping at DX centers was restored by raising the sample temperature to 160 K and then lowering it again. The increased temperature enables free electrons to overcome the energy barrier between the free state and the deep donor state and to be re-captured into the deep state.

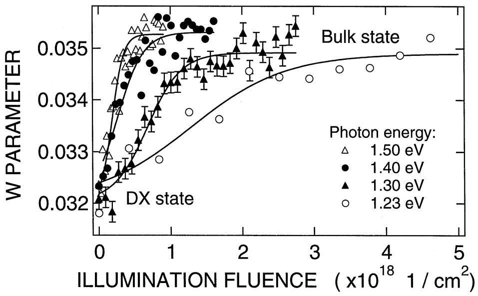

Fig. 2. The behaviour of the core annihilation parameter W as a function of the illumination fluence with various photon energies. The solid lines indicate fits (Eq. (3)) into the experimental data.

4.2. Results

Fig. 2 shows the measured W parameter as a function of the illumination fluence with four different photon energies. Before starting to illuminate the sample, the W parameter has a value characteristic to the positron trapping at DX centers (indicated in the figure as DX state). When the illumination is started, the W parameter is seen to rise very clearly indicating reduced trapping at vacancies. After the illuminating is continued long enough, the W parameter values are seen to saturate at certain level. At this point, the trapping at DX centers has stopped and the W parameter has the value characteristic of bulk annihilation.

The measured W parameter can be written in the form:

$$W = \frac{\lambda_b}{\kappa + \lambda_b} W_b + \frac{\kappa}{\kappa + \lambda_b} W_{DX}, \quad (1)$$

where W_b and W_{DX} are the characteristic W parameter values for positron annihilation in bulk lattice and for annihilation as trapped at DX centers, respectively. The trapping rate at DX centers, κ, is proportional to the concentration of DX centers and can be written as $\kappa = \mu N_{DX}$, where μ is the positron trapping coefficient for DX centers and N_{DX} is the number of DX center present in the sample. During the illumination, the number of the DX centers can be written as:

$$N_{DX}(t) = N_{DX}^0 e^{-\phi_{ph}\sigma^0 t}, \quad (2)$$

where ϕ_{ph} is the photon flux and σ^0 is the photoionization cross-section of DX center. By combining Eqs. (1) and (2) and writing $c = \mu N_{DX}^0/\lambda_b$, we get an equation:

$$W(t) = \frac{1}{ce^{-\phi_{ph}\sigma^0 t} + 1}\left(W_b + ce^{-\phi_{ph}\sigma^0 t} W_{DX}\right), \quad (3)$$

where the only unknown parameters are c and σ^0. By fitting Eq. (3) into experimental data, we get an estimate for σ^0. The fitted functions are indicated in Fig. 2 by solid lines. As can be seen from the figure, the saturation level varied a little from one measurement to another and in the fitting routine, the value of W_b was also left as fitted parameter.

The resulting photoionization cross-sections are shown in Fig. 3. For reference in Fig. 3, the results from photo-capacitance measurements are also shown [5]. The results from positron annihilation measurements can be seen to coincide quite well with the reference values. They seem to deviate only by a factor of 2–6, being higher throughout the studied photon energy range. With the photon energy of 1.1 eV, the measured cross-section can be seen to deviate clearly from the reference curve. With the photon energies smaller than 1.1 eV, the illumination times

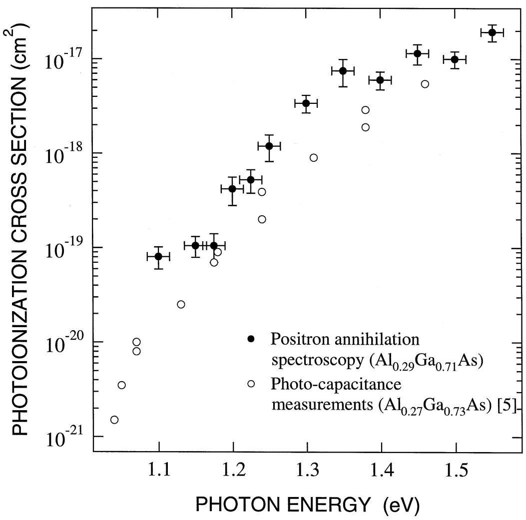

Fig. 3. The photoionization cross-sections calculated from the experimental data. Open circles are from photocapacitance measurement [6].

grew very long due to the limited maximum flux and no reasonable results were obtained. Long measurement at low temperature led usually to strong variation in annihilation parameter levels and as a result, the fitting procedure became very inaccurate. This variation in annihilation parameter levels is supposed to be caused by impurities which condensate on sample surface at low temperatures.

Two main sources of inaccuracy can be named in the measurement. The first and perhaps minor one is the estimation of the real intensity inside the sample. Our model, which was used for estimating the internal reflections, is very crude in comparison to the complex layer structure of our sample. The second source of inaccuracy is the effect of positrons on DX centers. If the sample was exposed to the positron beam for a long time, a similar effect was seen as in the case of the illumination. This is supposed to be caused by the hole capture at the DX center. During the thermalization, positrons generate electron-hole pairs. The DX center has been reported to have high cross-section for hole capture [6] and hole capture leads to a similar result as the photoionization. To reach the bulk level in annihilation parameters only by exposing the sample to positrons, measurement time of over 15 h was needed. The easiest way to minimize the effect of positrons would be to measure the annihilation parameters for each particular photon dose separately by restoring the DX population between every measurement point.

5. Conclusion

We have built a simple sample illumination facility for slow positron studies. The light is guided from the monochromator to the sample by an optical fibre bundle. The fibre bundle makes accurate intensity monitoring easy, although there still remains the difficulty in the estimation of the intensity inside the sample at a certain depth. The illumination facility was used to study the photoionization cross-section of the DX center in AlGaAs. The obtained cross-section values were found to coincide well with the results from other measurements. The result of the experiment shows that by combining the sample illumination to slow positron, it is possible to obtain quantitative information on optical properties of defects in semiconductors.

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