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Positron lifetime beam for defect studies in thin epitaxial semiconductor structures

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Abstract

Positron annihilation spectroscopies are methods for direct identification of vacancy-type defects by measuring positron lifetime and Doppler broadening of annihilation radiation and providing information about open volume, concentration and atoms surrounding the defect. Both these techniques are easily applied to bulk samples. Only the Doppler broadening spectroscopy can be employed in thin epitaxial samples by utilizing low-energy positron beams. Here we describe the positron lifetime beam which will provide us with a method to measure lifetime in thin semiconductor layers. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Positron spectroscopy; Vacancies; Instrumentation; Epilayers

1. Introduction

Positron spectroscopy is a method for direct identification of vacancy defects [1]. It is based on monitoring the 511 keV annihilation radiation emitted when thermalized positrons annihilate in solids with electrons. Positrons get trapped at neutral and negative vacancies because of the missing positive charge of the ion cores. At vacancies, the positron lifetime increases and positron–electron momentum distribution narrows due to reduced electron density.

The spectroscopy gives information on vacancies at concentrations 10^{15}–10^{19} cm^{-3}. Positron lifetime is a direct measure of the open volume of a defect. The Doppler broadening of the 511 keV radiation gives the momentum distribution of annihilating electrons $\rho_v(p)$. The core electron momentum distribution can be used to identify the sublattice and impurity surroundings of a vacancy. In addition, under varying temperature and illumination, the positron spectroscopy can yield information on charge states, optical transitions and thermal stabilities of vacancy defects.

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The lifetime and Doppler broadening are easily applied to bulk samples. Thin epitaxial semiconductor layers can also be studied by Doppler broadening spectroscopy using a positron beam. However, positron lifetime spectroscopy, which is essential for obtaining the open volume of the defect, has been mainly limited to bulk samples although some lifetime beams have been constructed [3,4]. The purpose of this work is to describe the need for a pulsed positron lifetime beam designed for the semiconductor studies. In Section 2, we discuss the conventional positron techniques. Section 3 describes the principle of the lifetime beam and Section 4 concludes this work.

2. Methods and background

In conventional positron lifetime spectroscopy (see Fig. 1), positron lifetime is defined as a time difference of gamma emitted in β^+ decay and the gamma emitted when electron–positron pair annihilates. The positron lifetime spectrum is composed of exponential decay components with intensities I_i and lifetimes τ_i as $\sum_i I_i e^{-t/\tau_i}$. The different exponential components are associated to annihilations at different positron states

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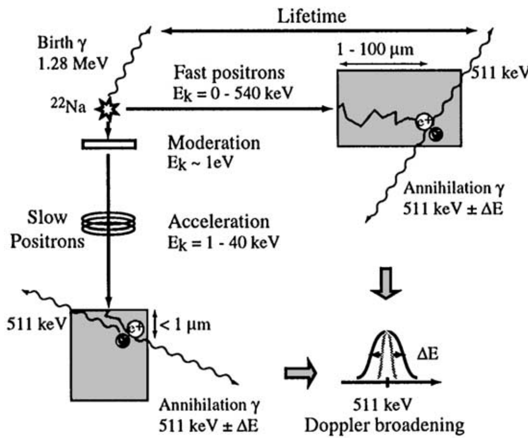

Fig. 1. The principle of positron experiment. Sources and measurable quantities.

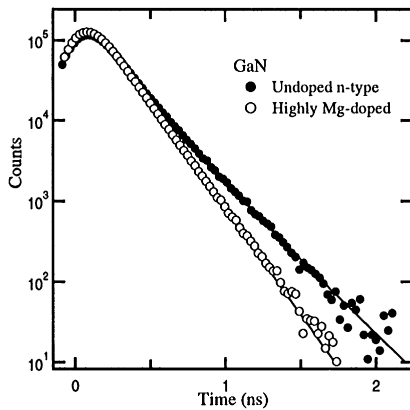

Fig. 2. Positron lifetime spectra from two different GaN bulk samples. In the highly Mg-doped sample (white circles) only one lifetime component 165 ps is present. In an undoped n-type sample a longer lifetime component of 235 ps is present due to vacancies [2].

(bulk vs. vacancy). This spectrum can be relatively easily decomposed and the individual lifetimes and their intensities can be extracted.

As an example in Fig. 2, two different lifetime spectra from undoped and highly Mg-doped GaN bulk samples are shown. In the highly Mg-doped sample only one lifetime component, 165 ± 1 ps can be observed. However, in an undoped sample a second lifetime component is present with a time of 235 ± 5 ps. This second component is due to Ga vacancies existing as native defects in n-type GaN. The intensity of the second component provides an estimate of vacancy concentration (10^{17} cm^{-3} in this case).

The average lifetime τ_{av} is defined as the center of mass of the lifetime spectrum,

$$\tau_{av} = (1 - \eta_V)\tau_B + \eta_V \tau_V = \text{C.M.}, \tag{1}$$

where η_V is the fraction of the positrons annihilating in the vacancies and τ_B is the bulk lifetime. It should be noted that τ_{av} is a statistically accurate parameter and changes below 1 ps can be measured.

In Doppler broadening experiments, the momentum distribution of the annihilating electrons is recorded by measuring the Doppler shift ΔE of the annihilation radiation with Ge-detector. The momentum distribution $\rho(p)$can be characterized by integrated S- and W-parameters shown in Fig. 3. The measured momentum distribution $\rho(p)$ is composed of the superimposed distributions from annihilations in vacancies $\rho_V(p)$ and in bulk $\rho_B(p)$ as shown in Eq. (2),

$$\rho(p) = (1 - \eta_V)\rho_B(p) + \eta_V \rho_V(p). \tag{2}$$

Very often this cannot be decomposed on its own. However, the decomposition is possible, if the annihilation fraction η_V and the bulk momentum distribution $\rho_B(p)$, determined by measuring a defect-free reference sample, is known.

In practice, the identification of the vacancies is based on measuring both τ_V and $\rho_V(p)$. τ_V is obtained from the decomposition of the lifetime spectra and it can be used to determine $\rho_V(p)$ (Eqs. (1) and (2)). This means that lifetime is normally needed for identification of vacancies. Furthermore, positron lifetime spectroscopy is approximately ten times more sensitive to defects than Doppler broadening spectroscopy.

The fast positrons emitted directly from ^{22}Na source have continuous energy range from 0 up to 540 keV and

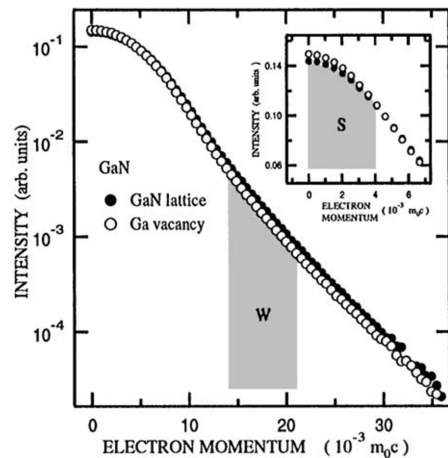

Fig. 3. Area normalized momentum distribution of annihilating electrons measured in Doppler broadening experiment. The S- and W-parameters, which are commonly used to describe the line shape, are defined as integrals over the shaded areas.

a wide implantation profile ranging up to 100 μm. In the conventional lifetime experiment bulk samples with dimensions of 5 mm × 5 mm and thicknesses > 100 μm are thus needed.

Slow positrons are obtained from ^{22}Na source by thermalizing the fast positrons in a moderator crystal (e.g. single crystalline W foil). The thermal positrons emitted from the surface of the moderator (energies less than 1 eV) are accelerated in an electric field up to 100 keV in order to study layers with thicknesses of 0–5 μm.

Both lifetime and Doppler broadening measurements can be done routinely with fast positrons. On the other hand, slow positron beam experiments are mainly limited to Doppler measurements. This is because the time information of the positron's entrance to the sample is lost in the beam formation. However, a low-energy pulsed positron beam enables the lifetime measurements in thin layers.

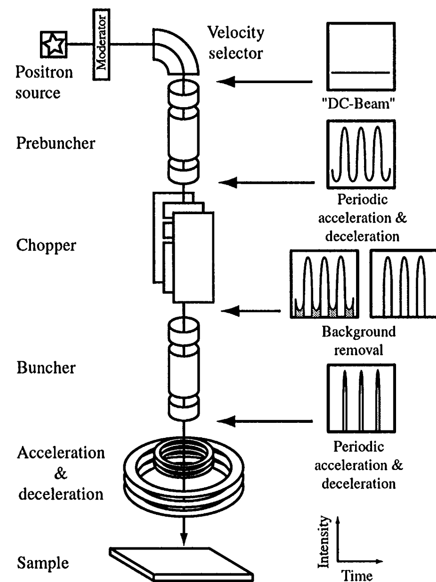

Fig. 4. The pulsed positron lifetime beam. Short pulses are used to measure positron lifetime in thin layers.

3. Positron lifetime beam

A successful method for positron lifetime measurements in thin layers is a pulsed positron beam [3,4]. In this system, the continuous slow positron beam is converted to very short pulses with a well-defined time structure.

In the following, we will describe the pulsed positron lifetime beam presently under construction in the Helsinki University of Technology [5]. Our beam has been designed especially for studies of defects in semiconductors. Unlike in the other existing systems [3,4], in our beam the sample is at ground potential to simplify its manipulation and temperature control. In addition, the sample can be illuminated to study the optical properties of the defects. Also, the beam energy is variable between 3 and 30 keV which enables the measurements of layers with thicknesses of 0–2 μm.

The principle of pulse generation is shown in Fig. 4. The positrons from a ^{22}Na source are thermalized in a W-foil moderator. Thereafter they are magnetically guided and further accelerated to a velocity selector, which separates the remaining fast positrons from the slow ones. This is done by solenoids and coils arranged perpendicular to each other. In the first pulsing stage, the prebuncher, two sinusoidial voltages (33 and 66 MHz) are used to periodically accelerate and decelerate positrons in two gaps between the middle electrode and the end electrodes. The electrodes are also biased so that positrons are accelerated with constant potentials across the prebuncher.

The prebuncher is followed by a drift tube where the energy-modulated beam compresses to pulses. After the drift tube, the first acceleration stage feeds positrons to the chopper, which is used to cut out the background between the pulses. This is done with three electrodes; the upper and the lower ones are grounded and the middle one is in an oscillating voltage with a frequency of 16.7 MHz. This voltage creates an electric field perpendicular to the beam, which increases the transversal velocity and the Larmour radius and makes positrons hit the walls of the chopper slit. By carefully adjusting the phase of the chopper voltage it is possible to cut out the background between pulses and pass the pulses through unmodified.

The main buncher is a resonating cavity with a frequency of 167 MHz. The two narrow spaces between the body of the cavity and the center electrode act as an acceleration–deceleration gaps. In this stage, the pulses are squeezed to a final width of 100 ps.

The pulses from the buncher are further accelerated by a constant voltage and slowed down to final energy in an adjustable decelerator before hitting the grounded sample. This kind of two-stage accelerator–decelerator structure is beneficial as it reduces the variation of the flight time through the acceleration stage with varying acceleration energies. It also helps to reduce the effects of the backscattered positrons in the lifetime spectrum. These positrons are accelerated away from the sample surface and they annihilate in the walls of the large chamber two or three nanoseconds after the arrival of the main pulse.

The pulse generation is controlled by electronics, which also provides the necessary timing signal corresponding to the time when positrons enter the sample. The timing signal for the positron annihilation is

measured by a BaF_2 scintillation detector placed behind the sample. The positron lifetime is obtained as a difference of these signals.

4. Conclusions

Positron annihilation spectroscopy can be used to identify vacancy-type defects in bulk semiconductor crystals and epitaxial layers. The identification of both vacancies and their surrounding atoms can be conventionally done only for bulk samples which can be measured with both lifetime and Doppler broadening spectroscopy. The pulsed positron beam described here will provide us with a method to measure positron lifetime in thin semiconductor layers. This enables direct identification of the open volume of the defect in the layer, more straightforward determination of vacancy concentrations, and improved sensitivity compared with Doppler measurements.

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