Title:

A positron annihilation lifetime measurement system with an intense positron microbeam.

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Abstract

An intense positron microbeam was formed using an electron linear accelerator. The beam is pulsed to apply positron lifetime spectroscopy to very small samples and to obtain positron lifetime images by scanning it. Positron lifetimes are measured with time resolution of less than 300 ps and with lateral spatial resolution of 30 - 100 μ m. A counting rate of the γ -ray to measure positron lifetime is about 10^3 s^{-1} which is 10 times higher than that achieved by the radioisotope based microbeam.

Keyword

slow positron, positron annihilation, positron lifetime spectroscopy, positron microbeam, positron microscope, positron probe microanalyzer

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1. Introduction

Positron annihilation spectroscopy (PAS) including positron annihilation lifetime spectroscopy (PALS) and Doppler broadening of annihilation radiation (DBAR) is a unique method to evaluate atomic scale defects in various materials (Kurause-Rehberg, 1999). Typical lateral spatial resolutions of PAS are about several mm, in which positrons from radioisotopes (RIs) or a slow positron beam with diameter of several mm are used. Therefore, PAS can be only applied to the samples which are greater than several mm in diameter.

In order to improve spatial resolution of PAS, positron microbeam system have been developed in which positron beams with diameter of $\sim 1 - 50 \text{ }\mu\text{m}$ were available (Brandes, 1988; Coleman, 2000; Egger, 2002; Fujinami, 2008; Haaks, 1999; Yu, 2007). Positron microbeams enable applying PALS and/or DBAR to very small samples and/or samples with small features of interest. In addition, positron microbeams have an excellent advantage. They can obtain PAS images by scanning injection position of the focused beams. The images allow the defect distributions to be visually evaluated.

For example, defects distributions around the fatigue and stress corrosion cracks of metallic samples were investigated by using PAS images (Egger, 2002; Haaks, 1999; Yu, 2007). Positron microbeams so far developed have used radioisotopes (RIs) as their positron sources, and consequently, their beam intensities are not sufficient. Many points of PAS measurements are necessary for obtaining its images, and hence, it takes rather long time (more than 1 day). Because of such long measurement time, microbeam PAS cannot be competitive with other analytical techniques.

Methods to produce a high intensity positron microbeam using an electron linear accelerator (LINAC) have been studied (Stoeffl, 1999; Oshima, 2008) to obtain the PAS images with shorter time. A method for focusing a LINAC-based intense positron beam was developed in AIST and a microbeam with diameter of $\approx 30 \text{ }\mu\text{m}$ was obtained (Oshima, 2009). The microbeam can be pulsed with two different kinds of pulsing system to measure positron lifetime. Therefore, both PALS and DBAR can be measured with high spatial resolution with high count rates. In this paper, positron microbeam system developed in AIST when it was applied for PALS is reported.

2. Positron lifetime measurement system with a positron microbeam in AIST.

2.1 Generation of a LINAC-based positron microbeam.

Our PALS measurement system with a positron microbeam is schematically shown in Fig. 1. An electron beam with an energy of 70 MeV from a LINAC is injected into a converter where an electromagnetic shower including fast positrons is produced. These fast positrons are immediately moderated through tungsten thin films and emitted as slow positrons into the vacuum (Akahane, 1990; Suzuki, 1997). These slow positrons are transported from the positron source to the experimental room by a magnetic transport system that is more than 20 m long in order to reduce the background radiation. The magnetic field formed along to a beamline in the magnetic transport system is about 7 mT. The beam energy is about 10 eV and diameter is more than 10 mm (Oshima, 2008). The beam intensity is about $2 - 3 \times 10^7$ e⁺/s which is two orders of magnitude higher than that of the RI-based beam (Coleman, 2000). At the end of the magnetic transport system, several kinds of experiments including PAS compared with ion backscattering (Kinomura, 2008), positronium time of flight (He, 2007) and positron-annihilation induced Auger-electron spectroscopy (Ohdaira, 1997) with intense positron beam are carried out.

A brightness enhancement system for the slow positron beam was built on a movable platform and can be easily connected to the end of the magnetic transport system. Since a magnetic focusing lens dose not effectively function in the solenoidal magnetic field, positron beams are once extracted from the magnetic field to the low (or no) magnetic field region with energy of 10 keV. A magnetic focusing lens was used in the low magnetic field region to effectively focus the positron beam. The positron beam with a diameter of about 30 mm was focused to ≈ 1 mm by the lens (Oshima, 2008). The brightness of the beam is enhanced by remoderating the focused beam using a transmission remoderator consists of a tungsten (100) thin film with thickness of 200 nm. The remoderation efficiency is about 5 %. The brightness-enhanced beam is extracted from the remoderator and injected into the sample through a center hole of a micro channel plates (MCPs) which detects back-scattered positrons and secondary electrons emitted from the sample. The beam is accelerated to a desired energy by acceleration tube electrodes and focused by a magnetic lens near the sample. The spot size of the positron beam on the sample was measured to be 30 - 100 μ m by a knife edge

method (Oshima, 2008; Oshima, 2009).

2.2 Pulsing system of a positron microbeam for positron lifetime measurement.

Time structure of the positron beam at the positron source is the same as that of the electron beam from the LINAC. The time width is ~ 1 s and the pulse rate is 100 pulses / s. The time width of the positron pulses should be stretched to prevent detector pile-up for PALS. One part of a magnetic transport system is assigned as a linear storage section (Akahane, 1990) where positron pulses are captured and confined radially by the magnetic field and longitudinally by electric potential gates. The captured positrons escape slowly from the linear storage section by gradually decreasing of the exit gate potential, as a consequence, the width of the positron pulse is stretched to several ms.

Timing information of positrons on samples is required in order to measure positron lifetime. Usage of a pulsed positron beam is one of solutions to know the positron injection time. Two pulsing system are installed in a positron beamline. The first pulsing system is installed at the end of the magnetic transport system and the second one is at the remoderator. The first pulsing system consists of a chopper, a pre-buncher and a buncher (resonant cavity) (Suzuki, 1991; Suzuki, 2000). The resonant frequency of the cavity is 165 MHz. A positron pulse of 10 ns width is chopped by a chopper and compressed by the pre-buncher and the buncher. Typical time width of positron pulse at the remoderator is about 400 ps. The pulse width of the brightness enhanced beam is further compressed by applying an RF (165 MHz) to the remoderator (Xu, 1997). Combination of a BaF₂ scintillator and a photomultiplier tube is used to detect annihilation γ -rays. Positron lifetime is defined by the time difference between the pulsing trigger signal obtained from the first pulsing system and the detection signal of the annihilation γ -ray. Figure 2(a) shows that the positron lifetime spectra when pulsed positron beams were injected into a stainless-steel. Time resolution is defined by the twice of the half width at the half maximum (HWHM) of the annihilation peak (see Fig. 2(a)). It is clearly seen that time resolution of the positron lifetime measurement system is improved by applying the RF to the remoderator. Best resolution so far achieved is ≈ 220 ps which is the same order of that obtained by the conventional PALS system. Positron lifetime spectra of tantalum and SiO₂ are shown in Fig. 2(b). The counting rate of the annihilation γ -rays are 10^3 s⁻¹ which is 10 times higher than that obtained by the

RI-based beam (Egger, 2002). By replacing the scintillation detector with a solid state detector, DBAR is also measured with this system. The AIST positron microbeam can drastically shorten the measurement time of PAS images and has a possibility to measure three dimensional PAS images by scanning the lateral injection position (in the xy plane) and the implantation depth (in the z direction) of the focused beam within reasonable time.

3. Conclusion

A high intensity positron microbeam produced by a LINAC was pulsed by two kinds of pulsing system for PALS with high spatial resolution. The developed system is also applicable for DBAR. Positron lifetime can be measured with time resolution of 220 - 300 ps and with lateral resolution of 30 - 100 μ m. The counting rate of the γ -rays to measure positron lifetime is about 10^3 s^{-1} which is 10 times higher than that achieved by the RI based microbeam. Speedy imaging of PAS is expected by scanning the intense positron microbeam in AIST.

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Figure captions:

Fig. 1. Schematic view of the PALS measurement system with a positron microbeam in AIST. An intense positron beam produced by a LINAC is focused by a focusing lens on a remoderator (W(100)) for enhancing its brightness. The brightness enhanced beam was extracted from the remoderator and is again focused at a sample. The beam diameter of the positron beam is 30 - 100 μm .

Fig. 2 Positron annihilation spectra measured by the positron microbeam. (a) The spectrum plotted by closed black circles (by open red circles) was measured when the 2nd pulsing system was turned on (off). It is clearly seen that system time resolution is improved by using the 2nd pulsing system (applying the RF to the remoderator). (b) Positron lifetime spectra of tantalum (closed black circles) and SiO_2 (open red circles) are measured with counting rates of $\approx 10^3 \text{ s}^{-1}$.