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Detection of re-emission positrons on metal surfaces during slow positron measurements

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Abstract. Detection methods for re-emitted positrons from Ni samples were investigated for in-situ positron annihilation lifetime spectroscopy during ion beam irradiation. A conventional mesh electrode and a ring electrode were examined to detect re-emitted positrons. Results of positron trajectory calculation were in good agreement with the experimental results on the mesh electrode. Simulation and experiments indicated that the ring electrode can form almost uniform electric fields in front of the sample and thus it can be used instead of the mesh electrode.

1. Introduction

It is well known that positrons have negative work functions for many metals [1]. When the positron work function is negative, some of slow positrons implanted into metals show diffusion to the surface and re-emission from the surface with kinetic energies corresponding to the absolute values of the work functions. Such unique characteristics of positrons are used in (1) positron moderators to obtain slow positron beams from high energy positron sources [1,2], (2) re-moderators for brightness enhancement to reduce positron beam sizes [3,4], and (3) re-emission microscopy [5,6]. In the re-emission microscopy including both transmission and reflection geometries, two dimensional defect distributions can be visualized due to the difference in re-emission yields between the defective and defect-free regions. Positrons in the defective region are preferentially trapped in defects and less positrons can diffuse to the surface, leading to a reduction in re-emission yield.

The method used in re-emission microscopy can be extended to in-situ positron annihilation spectroscopy under simultaneous ion beam irradiation. A dual-beam analysis system has been developed in AIST for in-situ positron annihilation lifetime spectroscopy (PALS) of ion-irradiation induced defects [7,8]. In this system, irradiation by pulsed ion and slow-positron beams can be controlled to investigate transient changes of irradiation-induced defects. Transient changes of defects were found to be detectable by re-emission yields as well as positron annihilation lifetimes. Thus, it is necessary to efficiently detect re-emitted positrons in PALS measurements during ion beam irradiation. In this study, detection methods for re-emitted positrons were investigated based on experiments as well as trajectory calculations and an optimum design for the dual-beam analysis system was proposed.

2. Experimental procedure

Positron experiments were performed at the AIST dual-beam analysis system for in-situ PALS during simultaneous ion beam irradiation [7,8]. This system consists of an electron linear accelerator (LINAC) based slow-positron beamline (positron source) combined with a small ion-accelerator (ion source). The electron beam from the AIST electron LINAC was used with pulse repetition rates of 25-50 pps. A slow positron beam was generated by a Ta converter and a W moderator and magnetically guided to the sample chamber. The positron beamline has pulsing electrodes (i.e., chopper, prebuncher and buncher electrodes) for lifetime spectroscopy. Annihilation gamma-rays were detected by a BaF_2 scintillation detector. Lifetime spectra were obtained by a fast waveform digitizer controlled by a personal computer [9]. An inert-gas ion beam (e.g., Ar^+ and He^+) was generated by the ion accelerator connected to the positron beamline with an acceleration voltage up to 150 kV. The ion-beam current was measured by a Faraday cup installed on the sample holder. The incident angle of the ion beam was 45º off the positron beam direction. Spot sizes of the positron and ion beams were approximately 1 cm and 1.5 cm in diameter, respectively. Mirror-polished pure Ni samples after annealing at 900 °C for 1h in vacuum were used in this study. The samples were heated to 500 °C to observe re-emitted positrons during the PALS measurements. Positron trajectory calculations were performed using the SIMION code [10].

Figure 1 shows the configurations of suppression electrodes around the sample holder used in this study. After the pulsing electrodes at the right-hand side (not shown in this figure), the positron beam is incident on the sample after passing through a drift tube and a cup electrode. The ion beam is also directed to the sample through a hole on the side of the cup electrode. Two type of suppression electrodes were installed in front of the sample to examine the effect of re-emitted positrons on lifetime spectra. The electrodes in figure 1 are cylindrically symmetric except for small parts including the ion-beam entrance hole of the cup electrode. The exit of the drift tube and positron-beam entrance hole of the cup electrode have meshes to ensure a uniform electric field for acceleration between two electrodes. High voltage (HV) was applied to the sample (sample holder) and the cup electrode to determine the final positron acceleration energy. A bias voltage to control the suppression electric fields near the sample was applied to the mesh- or ring-electrode.

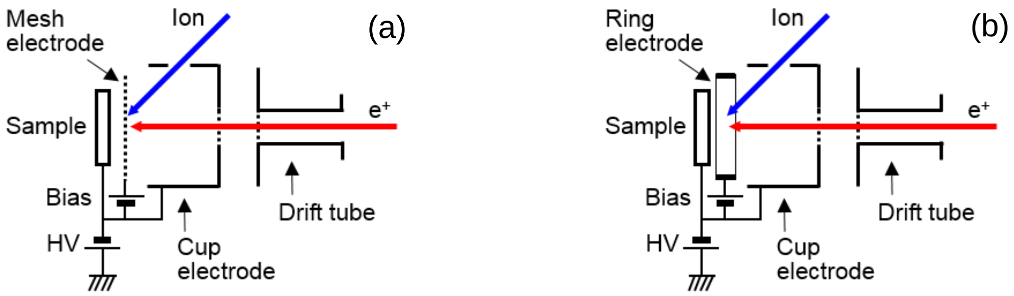

Figure 1. Configurations of suppression electrodes around the sample holder.

3. Results and discussion

Positrons re-emitted from the surface can be detected by using suppression electrodes that push re-emitted positrons back to the sample, leading to formation of satellite peaks in lifetime spectra. Suzuki *et al.* evaluated re-emission efficiencies for several remoderator materials and indicated that the positions of satellite peaks originating from re-emitted positrons depend on the bias voltage applied to the suppression electrode [2]. They used a mesh electrode as the suppression electrode to detect re-emitted positrons. When appropriate bias voltages are applied to the suppression electrode, incident positrons with an acceleration energy of several keV can go through the electrode but re-emitted positrons with energies of several eV are pushed back to the sample. The same type of the suppression electrode was used during the initial stage of this study as shown in figure 1(a).

The bias voltage applied to the mesh electrode of figure 1(a) was changed during PALS measurements of Ni with a positron energy of 2 keV. Figure 2 shows the PALS spectra of Ni as a function of the bias voltage, where E_p is the positron energy. When the bias voltage was 0 V, no appreciable peak was observed [figure 2(a)]. However, with a bias voltage of 2 V, a satellite peak was observed around 17 ns. With increasing bias voltage from 2 V to 20 V, the time difference between the primary peak (annihilation peak at 0 ns) and the satellite peak decreased [figure 2(b)]. This trend was exactly the same as that observed in the previous study [2]. Positrons re-emitted from the sample have kinetic energies comparable to the negative work function of the sample. Initially the re-emitted positrons are emitted in the opposite direction to the incident positron beam. However, such positrons are pushed back to the sample by the electric field formed by the suppression electrode, giving rise to another annihilation peak corresponding to flight times (i.e., satellite peak). Trajectory simulation for the re-emitted positrons were performed using the SIMION code. Structures of the sample holder and surrounding electrodes were modelled as closely as possible in the simulation. The electric field formed between the sample and the suppression mesh electrode was found to be uniform (not shown). Flight times of re-emitted positrons were plotted as a function of the bias voltage for three re-emission energies (0.5, 1.0 and 1.5 eV) in figure 3, together with experimental values from figure 2. The time of flight (vertical axis) decreased with increasing the bias voltage. The experimental values were in good agreement with the curve calculated for the re-emission energy of 1.0 eV. This value (1.0 eV) is comparable with the reported work function of Ni [1], although more precise measurements are required to determine the work function. At least, the results in figure 3 indicate that the SIMION simulation is effective to evaluate the suppression behavior of re-emitted positrons.

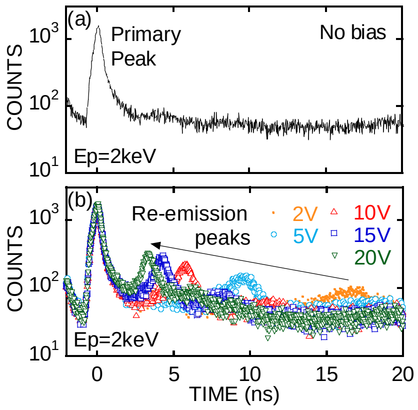

Figure 2. Positron lifetime spectra indicating re-emission peaks as a function of bias voltage to the mesh electrode.

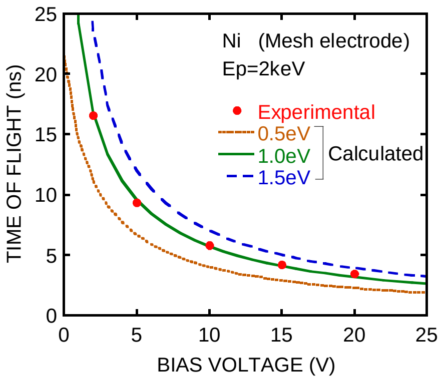

Figure 3. Calculated time of flight as a function of bias voltage to the mesh electrode for different re-emission energies.

The mesh electrodes were effectively used to observe re-emitted positrons. However, in the case of the dual-beam system, an ion beam is incident on the sample to introduce defects simultaneously with the positron beam for PALS measurements. If the ion beam hits the mesh electrode, it induces sputtering particles and secondary electrons from the mesh. Such secondary particles may negatively influence in-situ PALS measurements during ion beam irradiation. Thus, we introduced an alternative suppression electrode as shown in figure 1(b). This electrode with a ring shape allows us to introduce the ion beam without hitting a suppression electrode. It is easy to understand that the mesh electrode forms the uniform electric field for the suppression of re-emitted positrons, as it is a typical parallel-plate electrode structure. However, it is necessary to confirm the electric field formed by the ring electrode.

In the same way as the mesh electrode, the simulation for the ring electrode was performed to confirm the electric field and flight times of re-emitted positrons. Figure 4 shows the equipotential lines calculated by the SIMION code in the range of -5000 V to -4980 V (2 V step) when the bias voltage of 10 V was applied to the ring electrode. The structures shown in figure 4 include a rod to support the sample holder (upper side), a Faraday cup to measure ion beam current (lower side) and other supporting plates. The cup electrode was installed to reduce the irregular change of the electric field between the sample and the drift tube. The combination of the cup and ring electrodes successfully achieved the almost uniform electric field in front of the sample, as shown in figure 4.

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Figure 5 shows the positron lifetime spectrum of Ni at 500 °C with a bias voltage of 10 V. A positron energy of 5 keV was chosen to efficiently detect transient defect changes in in-situ PALS measurements. In addition to the primary peak at 0 ns, two satellite peaks were observed at 2.5 and 5.2 ns. The flight time of positrons re-emitted with an energy of 1.0 eV was calculated to be 4.6 ns, in reasonable agreement with the experimentally obtained value. The potential distribution formed by a ring electrode may be more sensitive to the small differences between the actual and the modelled electrode structures, compared with that of the mesh electrode. The simulation also showed that positrons backscattered at 2.5 keV form a peak around 2.5 ns. The satellite peaks observed in figure 5 can be attributed to the re-emitted and backscattered positrons. Thus, figures 4 and 5 showed that the ring electrode can be used instead of the mesh electrode to detect re-emitted positrons in lifetime spectra.

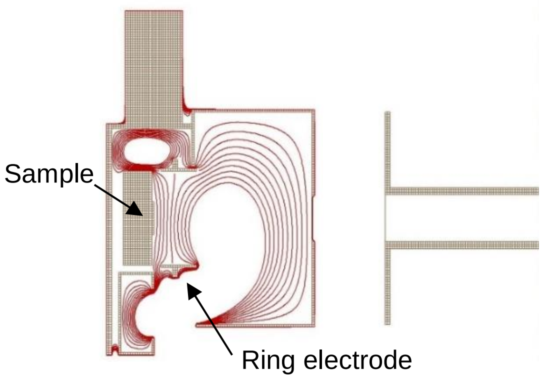

Figure 4. Equipotential lines (2 V step) calculated by the SIMION code for the ring electrode with a bias voltage of 10 V.

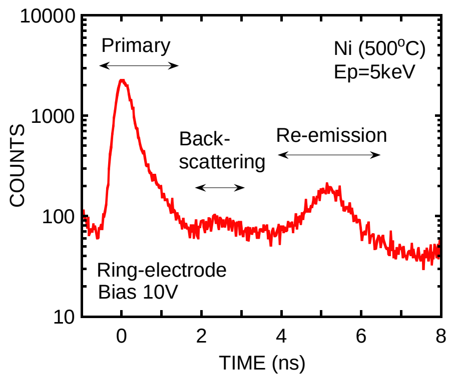

Figure 5. Positron lifetime spectrum of Ni at 500 °C with the ring electrode and bias voltage of 10 V.

4. Conclusion

Detection methods for re-emitted positrons were investigated for an in-situ PALS system during simultaneous ion beam irradiation. Mesh and ring electrodes were examined as suppression electrodes to detect re-emitted positrons from Ni samples. Positron trajectory simulation effectively explained positron flight times (i.e., satellite peak positions in lifetime spectra) in experiments with the mesh electrode. Both simulation and experiment showed that a ring electrode can be used instead of a mesh electrode to detect re-emitted positrons.

Acknowledgments

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[10] See for example http://simion.com/