4 The Slow Positron Facility

The Slow Positron Facility of the Photon Factory, equipped with a dedicated 55-MeV linac, provides a high intensity, pulsed slow positron beam. The linac operates in a short-pulse mode and a long-pulse mode, at frequencies of up to 50 Hz. The intensity of the beam has been increased tenfold to 5×10^7 slow positrons/s in the long pulse mode after improving the converter/moderator assembly for producing slow positrons in 2010 [1]. The pulse width in the short-pulse mode operation became adjustable from 1 to 10 ns in 2011, while that in the long-pulse mode remains at 1 μs. The facility is operated by a professor (Dr. T. Hyodo) and an assistant professor (Dr. K. Wada) who accommodate the research projects of users from other institutes and conduct their own research as well.

4-1 Production of Energy Tunable Positronium Beam

A method to efficiently produce the positronium negative ion (Ps^-), an exotic system composed of one positron and two electrons bound through Coulomb interaction, has been developed by Nagashima et al. [2,3]. The photodetachment of the Ps^- ions was accomplished on beamline SPF-A1 on those produced by the pulsed positron beam in this facility and a pulsed intense laser light [4,5]. Since a Ps atom is a neutral composite particle consisting of an electron and a positron, it cannot be accelerated by an electric field. However, photodetachment of the Ps^- provides a new technique for generating an energy-tunable Ps beam [6,7].

A new positron beamline branch, SPF-A3, was constructed for this purpose, where the beam is deflected by 45° along a curved magnetic field before it is incident on the target. The slow positron beam in the short pulse mode (intensity 5×10^6 slow positrons/s, width 12 ns, 50 Hz) was made incident on an annealed 25 μm-thick W foil coated with one monolayer of Na. The Ps^- ions emitted from the target were accelerated by an electrostatic potential of 0.5–2.8 kV. Then they were photodetached by using a photon pulse (width 12 ns, 25 Hz) from a Q-switched Nd:YAG laser to form energy-tuned Ps. BY synchronizing the laser pulse with every other slow positron pulse, it was possible to obtain data with the laser on and off simultaneously without concerning the fluctuation of beam intensity. The resulting *ortho*-Ps atoms traveled in the direction of acceleration of the Ps^- ions, and were detected by a pulse-counting mode MCP placed 80 cm away, squarely facing the W target. All the charged particles backscattered from the target were transported back along the curved magnetic field and were not detected by the MCP. Some of the γ-rays from the positrons annihilating in the target were detected by the MCP and gave information on the time of the Ps formation. The time interval between detecting the γ-ray and the Ps (time of flight, TOF) clearly showed that the Ps traveled with the energy expected from the electrostatic acceleration of the Ps^- ions.

Thus the generation of an energy-tunable Ps beam was accomplished. The energy range was 300 eV to 1.9 keV. Note that this beam is ultra-high-vacuum compatible and so can be used as a probe for solid surfaces.

4-2 RHEPD Experiments

Reflection high-energy positron diffraction (RHEPD), the positron version of reflection high-energy electron diffraction (RHEED), was proposed by Ichimiya [8] and was put to practical use by Kawasuso and Okada [9]. The station for RHEPD installed on the beamline branch SPF-B1 in 2010 has yielded 14 times greater intensity than the former measurements with the ^{22}Na based beam at the Japan Atomic Energy Agency (JAEA). The station has been used for studying surface structures. This is a project of Dr. Fukaya (Kawasuso Group) of JAEA.

Compared with electron diffraction, positron diffraction is easier to interpret: (1) the exchange interaction with electrons is absent; (2) the positron is not attracted into the vicinity of the nuclei since its charge is positive; (3) the surface sensitivity is high because the inelastic scattering cross section for the positron is high and the crystal potential for the positron is positive; and (4) the scattering factor for the positron has smooth angular dependence and falls off smoothly like that of X-rays because the positron is repelled by the nuclei. Thus, positron diffraction can be used to analyze surface atomic geometry with high reliability [10].

In RHEPD, in particular, we may take advantage of the existence of total reflection under conditions such as incidence of a 10-keV positron beam with a glancing angle of less than 2° on Si surfaces. This makes the normalized RHEPD intensity nearly two orders of magnitude larger than that of RHEED. This superiority extends smoothly to the region outside the total reflection region, making RHEPD a useful tool for surface structure analysis in spite of the difficulty of obtaining an intense positron beam. Another advantage of the total reflection is the extremely high sensitivity to the topmost layer of the solid surface. In fact, the present intensity of the beam in this facility already makes RHEPD as useful as other methods for surface structure analysis.

Fukaya and co-workers conducted many studies with RHEPD even with the ^{22}Na-based slow positron

beam. However, much effort was required because the beam intensity was not strong enough and so the counts had to be accumulated repeatedly for several tens of minutes even for orienting the sample crystal. The intense slow positron beam in this facility solves this problem; the beam is intense enough to orient the crystal in real-time.

One of the first results is the determination of the atomic configuration of well-ordered and defectless Pt-induced nanowires on a Ge(001) surface at low temperatures[11]. This research was performed in conjunction with scanning tunneling microscopy (STM) and angle-resolved photoemission spectroscopy (ARPES). Although the surface periodicity is known through STM measurements as p(4×2) at high temperatures (T > 110 K) and p(4×4) at low temperatures (T < 80 K), the detailed structures were not known and four possible models had been suggested. The present work examined the models and revealed that only one of them [13] reproduced the RHEPD rocking curve at low temperatures very well. The fundamental structure determined is that Ge dimers exist on the top layer and Pt arrays are buried in the second and fourth layers. At low temperatures (T < 80 K), each of the topmost Ge dimers is alternately tilted in the surface normal direction, making a p(4×4) periodicity. At high temperatures (T > 110 K), each Ge dimer is flat with respect to the horizontal axis, giving rise to p(4×2) periodicity. This demonstrates the extremely high sensitivity of RHEPD to the position of the surface atoms in the surface normal direction.

Temperature dependence of the specular spot intensity for the one-beam condition at θ = 2.5° was observed in the temperature range of 50–200 K. The intensity gradually increased between 80 K and 110 K, indicating the progress of the phase transition. This continuous change was reproduced by a power law; the order parameter is proportional to $|1 - T/T_c|^{\beta}$ with β = 0.36 ± 0.15 and T_c = 111 ± 10 K. The phase transition is explained as a displacive transition but the shift of the band dispersion is not directly related to a Peierls transition.

Another result of RHEPD experiments is the confirmation of the correlation of the spin splitting of the energy bands of Ag_2Pb surface alloy on an Ag(111) surface and the outward displacement of the Pb atoms[12]. This alloy is known to show a giant Rashba effect, *i.e.*, the energy split of the surface electronic bands due to the spin-orbit interaction is much larger than that of other similar systems. It was discovered in the present research that the position of the Pb atoms shifts depending on the thickness of the Ag(111) layer grown on the Si(111) surface. The shift of the position of the Pb atom for each Ag thickness was determined by using RHEPD rocking curves. Then the electronic states of Ag_2Pb alloy were investigated by using ARPES, while controlling the position of the Pb atom by changing the Ag(111) thickness.

Taken together, these results suggest that the magnitude of the Rashba energy depends on the outward displacement of the Pb atoms, as theoretically predicted [14]. They also suggest that the Rashba energy can be controlled by changing the Ag thickness of the substrate.

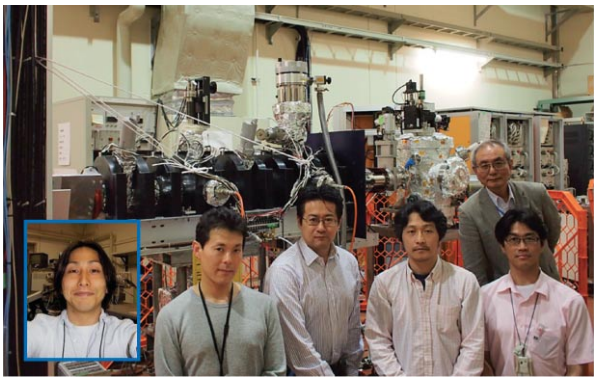

Figure 1
Construction of the RHEPD station on beamline SPF-B1.

4-3 Positronium Time-of-Flight Experiments

A new Positronium time-of-flight (Ps-TOF) station as shown in Fig. 2 has been installed on beamline branch SPF-A1 by Nagashima's group. It is equipped with two scintillation counters consisting of plastic scintillators coupled with photomultiplier tubes for high magnetic field environments. They are behind lead blocks with thin slits (one 2 mm opening at 40 mm away from the sample surface and the other with 6 mm opening 120 mm away).

Using this station, the emission of Ps from an Na-coated W film was investigated. The slow positron pulse

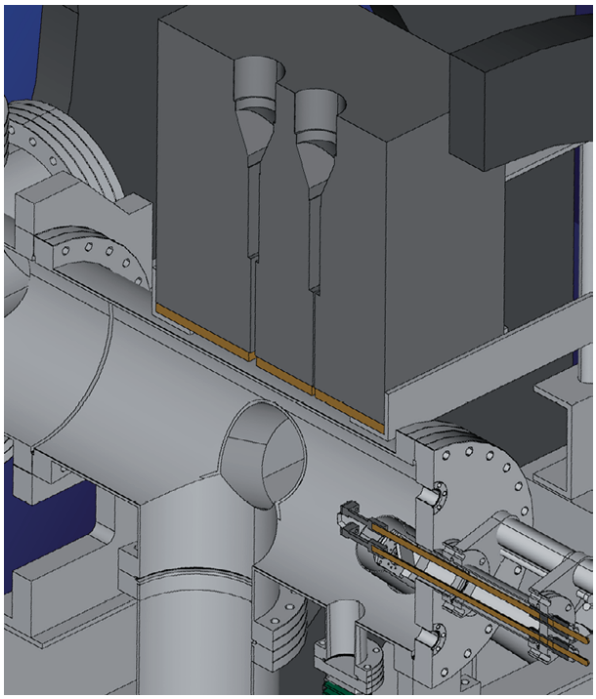

Figure 2
A cross section of the Ps TOF chamber on beamline APF-A1.

of energy of 4.2 keV was transported onto the target. The width of the positron pulse was 10 ns. A remarkable enhancement of the Ps yield was observed. The obtained TOF data provides information on the effect of the change of work function on the yield. The enhancement is tentatively attributed to the change in the electron density distribution near the surface, but the details of the TOF spectra are yet to be explained.

REFERENCES

[1] K. Wada, T. Hyodo, A. Yagishita, M. Ikeda, S. Ohsawa, T. Shidara, K. Michishio, T. Tachibana, Y. Nagashima, Y. Fukaya, M. Maekawa and A. Kawasuso, *Eur. Phys. J. D,* **66** (2012) 37.

[2] Y. Nagashima, T. Hakodate, A. Miyamoto and K. Michishio, *New J. Phys.,* **10** (2008) 123029.

[3] H. Terabe, K. Michishio, T. Tachibana and Y. Nagshima, *New J. Phys.,* **14** (2012) 015003.

[4] K. Michishio, T. Tachibana, H. Terabe, A. Igarashi, K. Wada, T. Kuga, A. Yagishita, T. Hyodo and Y. Nagashima, *Phys. Rev. Lett.,* **106** (2011) 153401.

[5] *Photon Factory Activity Report 2010,* **#28** (2012) A 68.

[6] K. Michishio, T. Tachibana, R.H. Suzuki, K. Wada, A. Yagishita, T. Hyodo and Y. Nagashima, *Appl. Phys. Lett.* **100** (2012) 254102.

[7] *Photon Factory Activity Report 2011,* **#29** (2012) A 60.

[8] A. Ichimiya, *Solid State Phenom*, **28-29** (1992) 143.

[9] A. Kawasuso and S. Okada, *Phys. Rev. Lett.,* **81** (1998) 2695.

[10] S.Y. Tong, *Surf. Sci.,* **457** (2000) L432.

[11] I. Mochizuki, Y. Fukaya, A. Kawasuso, K. Yaji, A. Harasawa, I. Matsuda, K. Wada and T. Hyodo, *Phys. Rev. B,* **85** (2012) 245438 .

[12] Photon Factory Activity Report 2011, **#29** (2012) B 73.

[13] D. E. P. Vanpoucke and G. Brocks, *Phys. Rev. B,* **81** (2010) 085410.

[14] G. Bihlmayer, S. Bl¨ugel, and E. V. Chulkov, *Phys. Rev. B,* **75** (2007) 195414.