Development on Positron Age-Momentum Correlation Instrument Using Digital methods

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Keywords : age-momentum correlation, positron annihilation, $CeBr_3$ scintillator, Digital method

1. Introduction

The age-momentum correlation (AMOC) technique has been developed to measure positron annihilation lifetime spectrometry (PALS) simultaneously and Coincidence Doppler broadening spectroscopy (CDBS) [1]. This technique enables non-destructive examination of materials to analyze microstructures and defects, such as crystal vacancy-type defects. AMOC studies primarily use plastic scintillators or BaF_2 scintillators for PALS. Plastic scintillators offer excellent time resolution but have poor energy resolution. In contrast, $CeBr_3$ scintillators and BaF_2 provide superior energy resolution than the plastic ones, allowing more precise measurements [2]. BaF_2 scintillators have a light yield of 1400 photons/MeV and exhibit both fast (0.6 ns) and slow (630 ns) decay components, while $CeBr_3$ scintillators have a higher light yield of approximately 68,000 photons/MeV. For CDBS measurement, a high purity germanium (HPGe) detector and one of $CeBr_3$ scintillators for PALS are aligned. In particular, advances in waveform digitization technology now allow the replacement of analog modules with fast digitizers. Given the limitations of analog AMOC methods, this study aims to develop AMOC measurement equipment using digital techniques.

2. Experimental setup and Specifications

The digitizer was the FADC500 (sampling frequency of 500 MHz, 12-bit) manufactured by Notice Korea. The maximum allowable voltage for the digitizer was 2.5 V. Waveform data were collected at a sampling time interval of 2 ns. Two $CeBr_3$ scintillators manufactured by Epic-Crystal are used in this study. It had a cylindrical structure with of 1 inch × 1 inch dimensions and was encapsulated in an aluminum case. The digital constant fraction timing method was employed for timing analysis. The digital method that can use offline data makes it possible to measure the correlation between the lifetime of positrons and the Doppler shift. $CeBr_3$ #1 provided the stop signal by detecting one of the 511 keV annihilation γ-rays. $CeBr_3$ #2 generated the start signal by detecting a 1.27 MeV nuclear γ-ray. The HPGe detector simultaneously measured the Doppler-broadened annihilation γ-ray energy spectrum by detecting the second annihilation γ-ray emitted in the opposite direction. The detector array was arranged with a ^{22}Na sealed source (5.08 μm thick Ti foil, Eckert & Ziegler) placed at the center. $CeBr_3$ #1 and $CeBr_3$ #2 were positioned at 90 degrees relative to the ^{22}Na source, and the HPGe detector was placed opposite $CeBr_3$ #1. The measurement samples were pure Si and polyimide. The total count of the measurement sample was 3×10^7 counts.

The ^{137}Cs and ^{22}Na sources were used to measure the energy resolution, which was determined by measuring the full width at half maximum (FWHM) of the full energy peaks. The accumulated histogram of the primary pulse amplitude was calibrated using the known energies of the ^{137}Cs (662 keV) and ^{22}Na (511 keV and 1,274 keV) standard source. The time resolution was determined by coincidence recording the full energy peaks of 1173.2 keV and 1332.3 keV emitted from a ^{60}Co standard source and analyzing the zero-crossing point using the digital constant-fraction discriminator (dCFD) method [3]. The measured time resolution ($FWHM_T$) is (0.36 ± 0.1) ns.

Table 1. The energy resolution of each detector.

Energy (keV)	$CeBr_3$ #1 (%)	$CeBr_3$ #2 (%)	HPGe (%)
511	10.40	9.81	1.77
662	8.73	8.21	1.17
1274	6.09	5.65	0.74

3. Results and Discussion

A device capable of analyzing the time-dependent behavior and energy distribution of positrons in pure Si and polyimide materials was successfully developed. Figure 1 shows the AMOC relief of the polyimide sample. The experimental results in Fig. 2 clearly illustrate the time distribution of positron annihilation characteristics in the pure Si and polyimide samples. The positron annihilation profiles of pure silicon and polyimide are distinctly different, with polyimide exhibiting a broader positron lifetime distribution than pure silicon. These results demonstrate that the developed device can precisely analyze positron annihilation characteristics based on the microstructure of materials, indicating its potential as a valuable tool for studying various material properties.

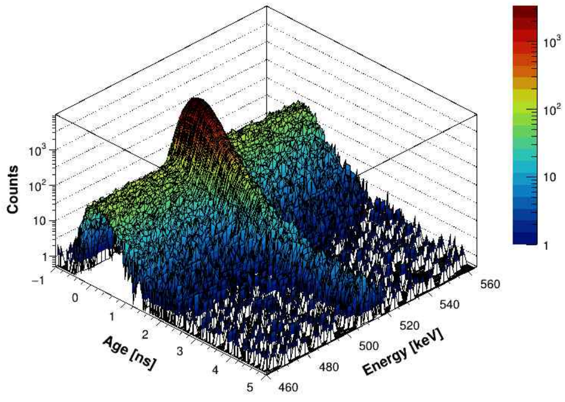

Fig. 1. Positron age-momentum correlation (AMOC) relief of polyimide measured at room-temperature.

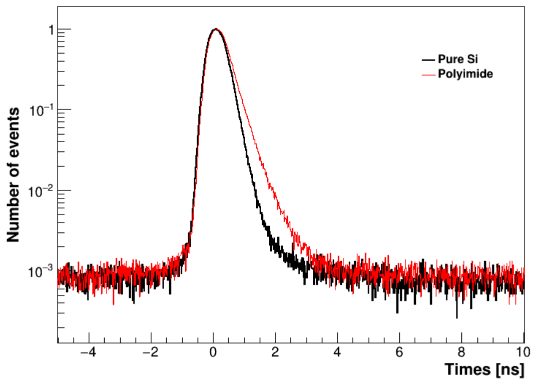

Fig. 2. Positron lifetime spectra of pure silicon and polyimide.

4. Conclusions

Digital-based positron age-momentum correlation data was obtained using the CeBr3 scintillator and HPGe detector. The experimental results revealed that our developed AMOC device can distinguish the correlation between positron lifetime and momentum. In the future, the AMOC instrument will be used to measure various samples, including neutron-irradiated silicon, germanium, silicon carbide, and different polymer materials. Material analysis studies for each sample will be conducted, further demonstrating the potential of the AMOC technique as a valuable tool for studying various material properties.

Acknowledgment

This work was supported by the Korea government (MSIT) (1711078081)

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