First Experiments with the MePS system

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Abstract: MePS (Mono-energetic Positron System) is part of the EPOS system (ELBE Positron Source) in the HZDR (Helmholtz-Zentrum Dresden-Rossendorf). It is one of the installations at ELBE (Electron LINAC for beams with high Brilliance and low Emittance), which supplies a 40-MeV electron beam. MePS makes use of the excellent time structure of the primary electron beam of ELBE (repetition frequency up to 26 MHz; bunch length < 5ps) to produce a pulsed, intense slow positron beam to allow positron lifetime spectroscopy. In order to avoid spurious signals, which, in other systems, are often obtained by positrons reflecting from the sample surface, a bent tube (45°) was added between accelerator and sample chamber. The MePS system has been used to study the pore system of a series of low-k dielectric layers.
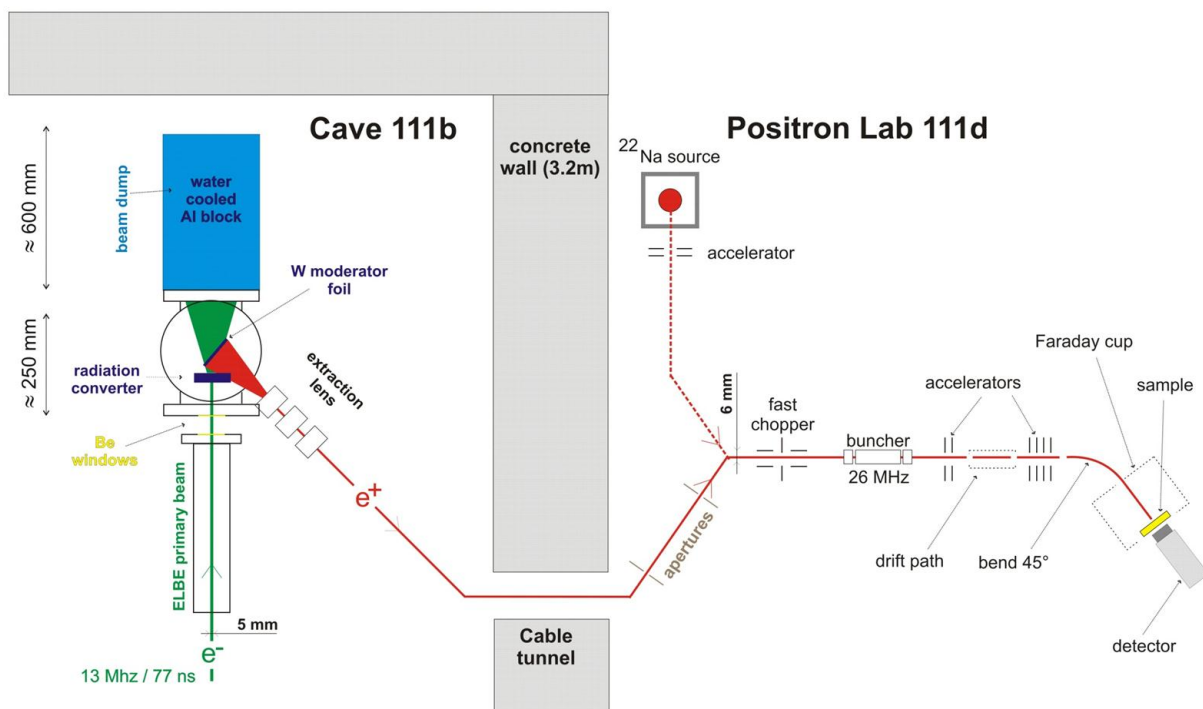
1. Introduction

MePS is a user-dedicated, highly-intense, bunched beam system using mono-energetic positrons for materials research with positrons and positronium. The MePS system is now almost finished. We started the setup at ELBE in December 2007 and we preliminary finished it in September 2011. After changing the moderator from a Pt foil to a stack of tungsten foils with 10 tungsten meshes on top, we gained a factor of 20 in intensity. The count rate at the output of the photomultiplier, which is located close to the sample (separated only by the glass of a view flange), was 25000 cps (25 µA at 30 MeV electron beam power = 750 W). At ELBE's maximum power of 40 kW (1mA at 40 MeV), a count rate of several 10^5 cps is to be expected. There are plans to increase the maximum average current in the future to 2 mA. The chopper pulse generator is not yet available, so the time resolution is only about 500 ps. However, this time resolution is sufficient for porosimetry investigations. First experiments were done to study low-k dielectric layers.

2. The setup of the MePS system

The ELBE electron beam has a unique time structure: very short electron bunches (< 5 ps) hit the electron-positron converter in cw-mode with a frequency of $26/2^n$ MHz (n = 0,1,2,…) in Cave 111b. The repetition frequency can be adjusted according to the requirements: 77 ns is used for positron lifetimes, while very long lifetimes can be measured by 616 ns repetition time (porosimetry with positronium). In the latter case, a higher bunch charge can be applied, so that the intensity will not decrease. A scheme of the system is shown in figure 1. The converter consists of a stack of 50 tungsten foils (0.1 mm each), which is water-cooled directly. A beam dump made from 5N-Al stops

the electrons after they have passed the converter. The moderator is located in front of it and parallel to the entrance window of an Einzel lens. The moderated positrons are extracted by the transport energy of 2 keV. The lens focuses the positron bunch into a longitudinal magnetic guidance field. More than 30 steering coil pairs allow the adjustment of the beam inside the beamline at any position. The beam is fed from the cave 111b through a cable tunnel into the positron lab (cave 111d). The tunnel lies beneath a 3.2 m shielding of heavy concrete. Although the electron and thus the positron bunch is very small after pair production, when the bunch arrives in the lab 6 m away it is broader (about 10 ns). This is due to the moderation process, inhomogeneity in the acceleration field, and different paths in the beamline (three bends). Thus, a combination of chopper and double-slit buncher are needed to improve the timing. The chopper cuts a 4 ns window into the bunch, and the buncher will produce the time focus at the sample position.


Figure 1. The scheme of MePS. Positron production in Cave 111b and the positron lab (Cave 111d) are separated by a 3.2 m concrete wall. The beam length is about 12 m [1,2].

The shift of the time focus due to different acceleration voltages is compensated by a different velocity in a drift path and also by different RF-amplitudes in the buncher. After an additional beam bend of 45° (see discussion below) the sample is mounted in a Faraday cup. The PMT (Hamamatsu H3370-50) is located close to the sample but outside the vacuum, separated only by the glass of a viewing window.

3. Solving the problem of backscattered positrons
For high-z sample material, a large fraction of positrons is scattered back into the beamline [2]. They are guided by the longitudinal field until they reach the accelerator. There, they will be re-accelerated to the sample and, thus, will produce side peaks in the lifetime spectrum. Usually, an additional E×B filter in the beamline shall suppress these artifacts. However, this suppression is never complete. We used another approach: a 45° bend after the accelerator is equipped with steering coils. They guide the bunch through the bend to the sample, but they will not allow the backscattered positrons to reach the accelerator. They will hit the wall away from the detector. Figure 2 shows the effect of this filter: in the left panel the lifetime spectrum of a Cu sample is shown in a straight setup (no bend). The accelerator is working and one can clearly see a strong side peak about 70 ns after the main spectrum.

In the right panel, the bend is mounted, and the sample was measured under otherwise identical conditions. The effect is clearly visible: there are no longer any spurious signals, and, in addition, the background is distinctly reduced.
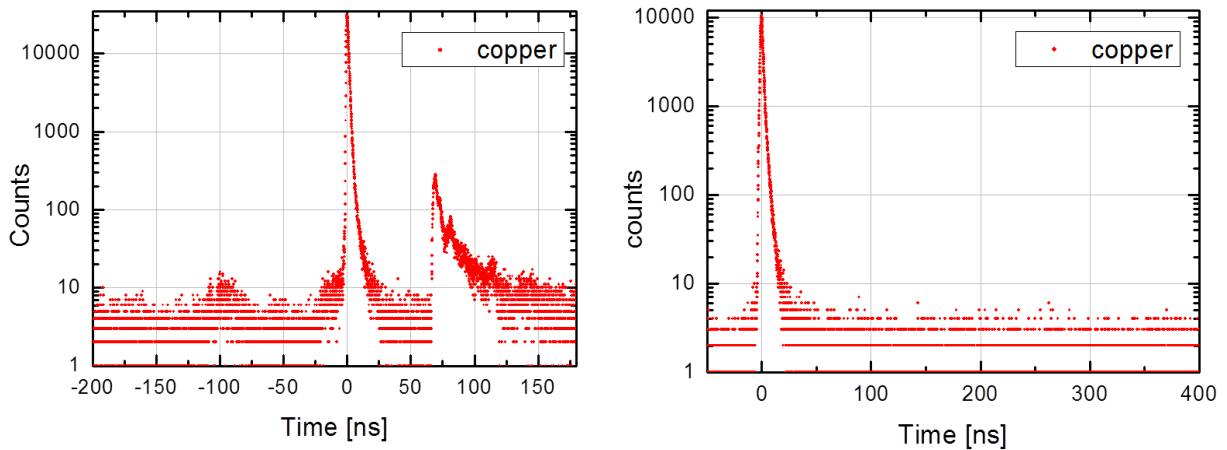
Figure 2. Lifetime spectra of Cu in a straight setup (left panel) and after assembly of a 45° bend into the beamline between accelerator and sample (right panel).

4. Simulation of the required chopper pulse
In order to specify the necessary pulse width for the chopper pulse, we performed an over-all time-dependent simulation with SIMION 8 from the moderator to the PMT.
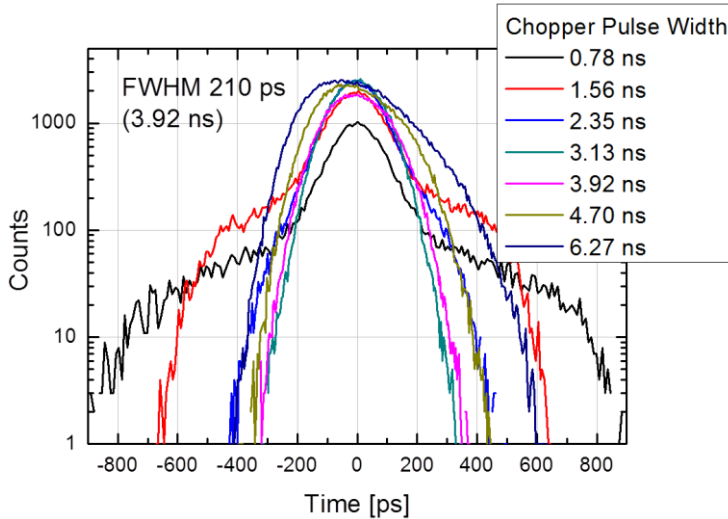

Figure 3. The simulated time structure at sample position as function of the width of a Gaussian chopper pulse. A pulse width of 4 ns is still acceptable.

Figure 3 shows the simulated time structure of the positron beam at the sample position for different chopper pulse widths. For a width of 3.9 ns, a time resolution of 210 ps is to be expected (contribution of PMT is included). Thus, the pulse generator must provide pulses with 13 MHz, 100V amplitude and a width of 4 ns and a nearly Gaussian shape. This demand should be realizable. In case of problems due to the high repetition frequency, one could use 616 ns (1.625 MHz) as standard mode for the lifetime measurements. For high count rates ($> 10^5$), however, the intensity of long lifetimes can be decreased due to multiple hits of the detector during one bunch. Certainly, this disturbance can be corrected.

5. First use of MePS: Study of low-k dielectric layers

Low-k insulating layers are used to reduce the product R×C in ULSI integrated circuits in order to allow for higher clock frequencies. As a first experiment at MePS, we studied a set of such low-k dielectric layers, which were prepared variously.
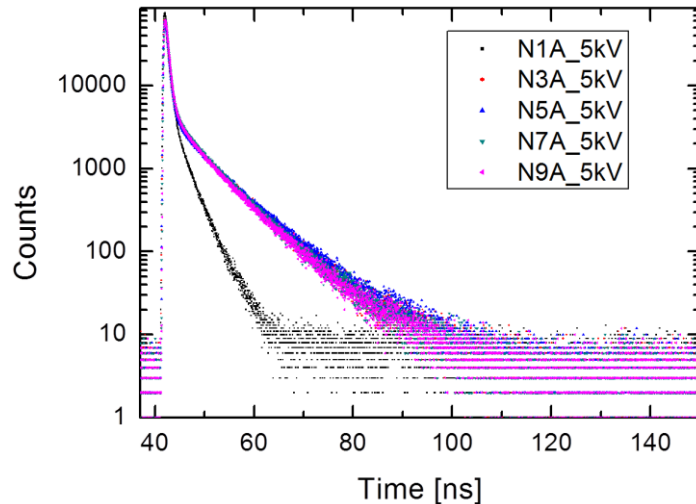
Figure 4. Positron lifetime spectra of 1 μm low-k layers measured at 5 keV (about 450 nm positron penetration depth). The samples were variously treated: as-received (N1), variously plasma treated (N2, N3) and with an additional TiN cap layer (N7, N9).

The samples were CVD grown with a low-k layer thickness of about 1 μm. Figure 4 shows the comparison of the spectra accumulated at 5 keV corresponding to a mean positron penetration depth of 450 nm. The spectra show hardly any spurious signals in the background. The peak-to-background ratio is about 10^4. The spectra were recorded without the chopper (chopper plates grounded). Thus, the original pulse has only been treated by the buncher. The time resolution is 500 ps (FWHM), which is sufficient for porosimetry. The observed pore size at this particular depth was 0.68 nm for the untreated sample and 1.12 to 1.18 nm for the treated samples.

6. References

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