Efficient positron moderation with a commercial 4H-SiC epitaxial layer

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Abstract. We have studied the properties of a commercially available 4H-SiC epitaxial layer and evaluated its potential application as an efficient positron remoderator. A remoderation efficiency of more than 65% has been measured for incident positrons with 1 keV energy. We have determined the work function and the energy distribution of the emitted slow positrons, a property which is essential for practical applications. Comparison of the positron moderation properties of the epitaxial layer with results from a n-type 4H-SiC single crystal, indicate that the epitaxially grown layer is a superior secondary moderator than its substrate counterpart.

1. Introduction

Slow monoenergetic positron beams rely on radioactive or pair creation sources. Positrons are moderated by a dense material with negative work function for positrons, or a solid rare gas.

It has been long established that n type silicon carbide is an efficient moderator material [1], although its low density makes it unsuitable to be used as a primary moderator. Previous work by Suzuki et al. [2] suggests that an epitaxially grown 6H-SiC film with a low carrier density is a good candidate for a secondary moderator. Other studies on as grown SiC wafers have shown the potential of this material, but revealed a small remoderation efficiency in comparison to the epitaxially grown wafers [3][4]. Today, large (10 cm) good quality epitaxial wafers are readily available with a very low carrier concentration and defect density, due to improvements in layer growth technology and defect control.

In this paper we present measurements on the remoderation properties of a commercial 4H-SiC epitaxial layer, and show that it can be efficiently used as a positron secondary moderator.

2. Experimental setup

We used the positron beam facility at Irfu/CEA Saclay, France [5]. It consists of a small linear electron accelerator (linac) that generates 4.3 MeV electrons in 2.5 µs long pulses with 200 Hz repetition frequency. The electrons hit a tungsten target, producing gamma radiation by Bremsstrahlung, which induces positron-electron pairs. Directly behind the target there is a stack of well annealed thin tungsten meshes that is used as a moderator. The positron moderator slows down the high energy positrons to a few eV kinetic energy range. A pulsed beam of slow positrons (~ 50 eV) leaves the moderator structure and is adiabatically transported in a 8 mT
A magnetic field, generated by solenoids wound around the vacuum tube. We routinely obtain a positron flux of $2 \times 10^6 e^+/s$. A positron pulse stretcher forms a quasi-continuous beam from the 2.5 $\mu$s pulses generated by the linac. It is a low-field Penning-Malmberg trap with three electrodes. The second electrode is 4 m long, in order to accommodate the entire slow positron pulse. The other two electrodes are open and close the trap, synchronized with the linac pulses. For this setup the voltage pulse applied to the exit electrode of the stretcher was modified to produce short positron pulses ($\sim 100$ ns FWHM).

Near the target the positron beam is accelerated at the entry of a 30 cm tube, kept at a negative bias $V_{\text{tube}}$, and hits a 4H-SiC epitaxial layer held at a bias $V_{\text{sample}}$. The epitaxial layer was grown on a n-type 4H-SiC (0001) substrate, with 16-28 m$\Omega$ cm resistivity, and is nitrogen doped with a carrier density smaller than $10^{15}$ cm$^{-3}$, and 5.5 $\mu$m thick. It was purchased from Norstel. The epitaxial layer was not subjected to any form of surface treatment, it was used as received. The detection of the photons resulting from the annihilation of the positrons was done by means of a plastic scintillator.

All measurements reported were performed on the epitaxial layer and on the SiC substrate (backside of the 4H-SiC wafer).

**Figure 1.** Scheme of the experimental setup. A 30 cm length tube held at $V_{\text{tube}}$ accelerates the positrons onto the 4H-SiC target with a bias $V_{\text{sample}}$.

### 3. Results and discussion

Since 4H-SiC has a negative work function $\Phi^+ \sim -2$ eV [3][4], incident positrons are re-emitted from the surface. If their energy is high enough to overcome the potential difference between the tube and the sample ($\Delta V$), they can execute several round trips between the sample and the end of the tube, while a fraction of positrons is annihilated at the target in each trip. This process can be observed in Figure 2 for both the epitaxial layer and substrate. In here $V_{\text{sample}}$ was set at -2000 V and $V_{\text{tube}}$ was varied. One observes that the time it takes the positrons to do a round trip increases with increasing $\Delta V$, due to the decreasing energy of the re-emitted positrons.

A remoderation efficiency, ratio of the number of re-emitted positrons to the number of incident positrons, higher than 65% has been obtained for 1 keV positron energy while for the substrate the maximum efficiency is 60%. The positron re-emission yield ($Y$) is defined as the fraction of the incident positron beam that was remoderated $Y = 1 - \frac{A_1}{A}$, where $A_1$ is the integrated area of the first positron annihilation peak (Figure 3), when remoderation occurred, and A the integrated area of the total annihilation peak (i.e the tube was set at -1995 V, hence all the positrons were annihilated).

The work function $\Phi^+$ was measured by setting the sample at -2000 V, and varying the tube voltage from -1900.5 V to 2010.6 V. Figure 4 shows the re-emission yield as a function of the voltage.
Figure 2. Signal obtained by the photomultiplier for the epitaxial layer (right) and substrate (left) for different voltage differences between the tube and the SiC sample. The energy of the incident positrons is 2 keV. The curves were shifted vertically for clarity.

Figure 3. The positron re-emission yield (Y) is defined as the fraction of the incident positron beam that was remoderated. $A_1$ is the integrated area of the first positron annihilation peak, when remoderation occurred, and $A$ the integrated area of the total annihilation peak.

of the voltage difference between the tube and the sample ($\Delta V$). The data was fitted to the complementary error function. The positron work function $\Phi^+$ can be found by subtracting the bias for which all the positrons emerge from the sample and the bias corresponding to the point of steepest descent of Figure 4. We have measured $\Phi^+ = -2.1$ eV for the epitaxial layer and $\Phi^+ = -2.7$ eV for the substrate, in agreement with the results of [3] and [4].

We can obtain the energy distribution of the surfacing positrons by differentiating the complementary error function. These had an energy spread of $\sigma = 0.91$ eV $\pm$ 0.05 eV for the epitaxial layer and $\sigma = 1.13$ eV $\pm$ 0.09 eV for the substrate.

The positron re-emission yield was also measured as a function of the incident positron beam energy. Our results were fitted using the program VEPFIT [6] to calculate the probability distribution, $P(E_{e^+, z})$, as a function of the depth $z$, implantation profile and effective diffusion length $L$. We obtained an effective diffusion length of $L = 267$ nm for the epitaxial layer and
L = 51 nm for the substrate. The smaller diffusion length of the substrate is consistent with a higher amount of defects that trap the positrons. Furthermore, we observed a higher yield for a larger positron energy range for the epitaxial layer, which can be an advantage for large energy spread beams.

![Figure 4](image-url)  
**Figure 4.** Positron re-emission yield as a function of the voltage difference between the tube and the SiC sample (ΔV) for the substrate.

Although the kinetic energy distribution of the remoderated positrons is significantly broader than that of the best single crystal metal moderators, high efficiency and easy handling makes SiC an attractive alternative in many cases where significant improvement is needed in brightness but narrow energy distribution is not essential. Such cases are when brightness enhancement is needed after a positron buncher with large amplitude or positron ejection from an accumulator with a deep potential well.

4. Conclusion
We demonstrate that a commercially available n-type 4H-SiC epitaxial layer grown on a SiC substrate is an efficient positron remoderator. A remoderation efficiency higher than 65% has been measured for 1 keV implanted positrons. The measured work function Φ⁺ = -2.1 eV is in good agreement with [3] and [4].

Our results indicate that the epitaxially grown layer is a superior secondary moderator than its substrate counterpart. Being easily available and requiring minimal maintenance makes the epitaxial 4H-SiC an attractive solution for positron moderation, facilitating the construction of laboratory-based positron beams with higher beam intensity and brightness.

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