Tungsten mesh as positron transmission moderator in a monoenergetic positron beam

H.M. Weng a,b, C.C. Ling a,*, C.D. Beling a, S. Fung a, C.K. Cheung a, P.Y. Kwan a, I.P. Hui a

a Department of Physics, The University of Hong Kong, Pokfulam Road, Hong Kong
b Department of Modern Physics, University of Science and Technology of China, Hefei, China

Received 17 March 2004; received in revised form 28 April 2004

Abstract

The slow positron yield has been measured for various tungsten (W) moderator samples from a $^{22}$Na radioactive source. Multi-folded W mesh, W(1 0 0) single crystal foil and W polycrystalline foil samples have been investigated. It is found that the fast to slow conversion efficiency of the W mesh moderator depends on: (1) the annealing pretreatments, (2) the chemical etching duration and (3) the number of the folding layers. With the raw W mesh material having a wire diameter of 20 $\mu$m and transmission efficiency of 92.5%, an optimal efficiency of $1.2 \times 10^{-3}$ was achieved with 5 min etching duration and a folding number of 12 layers.

© 2004 Elsevier B.V. All rights reserved.

PACS: 79.20.Mb; 78.70.Bj

Keywords: Positron emission; Positron moderation; Tungsten mesh; Positron annihilation

1. Introduction

Slow energy positron beam facilities have been used in many applications, for example in the fields of atomic physics and materials sciences, and detailed reviews of positron beam technique and the corresponding applications can be found in [1] and [2]. The slow positrons are obtained by moderating the high energy positrons, which originate either from the radioactive isotope $\beta^+$ decay process or from the accelerator based pair production process, with materials that have negative positron work functions. As the work function for positron and electron are given by: $\phi = D - \mu$, where $D$ is the surface dipoles and $\mu$ is the chemical potentials for positron or electron accordingly, the positron work function is possibly negative, while it is always positive for the electron, because $D$ is positive for electrons and negative for positrons. After the high energy positrons are implanted into the moderator, they rapidly thermalize within period shorter than $\sim$10 ps and undergo diffusion. A fraction of diffusing positrons arrives at the surface and a fraction of these emits into the vacuum if the positron work function of the surface is negative.
The efficiency of a moderator is thus dependent on a number of factors, namely the fraction of positrons arriving at the emitting surface, the probability of the positron emitting from the surface and the geometric configuration of the moderator.

As compared to the solid noble gas moderator having the efficiency of $7 \times 10^{-3}$ [3], the conversion efficiency of the tungsten moderator ($\sim 10^{-4}$–$10^{-3}$) [1,2] is not so attractive. However, tungsten is one of the most commonly used moderator material because of its reasonable efficiency, its high positron work function and its stability for working in the environments of high vacuum or ultra-high vacuum. For the transmission source-moderator geometry, single crystal and polycrystalline W foils have been used extensively as moderators [4–8]. The fast to slow conversion efficiency of such moderators has been reported to be $\sim 5.9 \times 10^{-4}$ [5]. Saito et al. [9,10] have also demonstrated the use of multi-folded W mesh as the transmission moderator and obtained an efficiency as high as $\sim 7.5 \times 10^{-4}$. With the use of tungsten filaments from commercial light bulbs, Liszkay et al. [11] have achieved an efficiency of $4 \times 10^{-4}$, which is comparable to the efficiency of an expensive single crystal foil.

Although conversion efficiencies using different forms of W have been previously reported, comparisons between data from different positron beams are difficult because the reported efficiency not only depends on the moderator, but also depends on geometrical factors involved in the beam design. In the present study, with fast positrons implanted from a $^{22}$Na radioactive source, we have investigated and compared the fast to slow positron conversion in the cases of the multi-folded W mesh moderator, the W(100) single crystal foil moderator and the W polycrystalline foil moderator. The influences of sample pretreatments, the duration of chemical etching and the number of folding layers in the case of the W mesh moderator have also been investigated.

2. Experimental

The moderator efficiency measurements were carried out with the compact positron beam located in The University of Hong Kong [12,13]. Small amendment was made to convert the source-moderator configuration to the transmission moderator geometry. The positron source used was 200 $\mu$Ci Na$^{22}$Cl deposited onto the tip (diameter 3 mm) of a stainless steel rod. An accelerating potential is applied across the moderator and the grid, which is placed in front of the moderator, so as to accelerate the emitted slow positron from moderator surface. The positrons are then transported through the guidance of a 30 G magnetic field. The positrons then pass through or are reflected by a retarding field energy analyzer (RFA). On passing through the RFA they are detected by the channel electron multiplier (CEM) detector having an effective detecting diameter of 10 mm. The slow positron emission measurements were performed in the vacuum of $2-4 \times 10^{-6}$ Pa. The conversion efficiency of the moderator is defined as: $\varepsilon = N_{\text{slow}}/N_{\text{fast}}$, where $N_{\text{slow}}$ is the count rate of slow positrons emitted at the moderator and $N_{\text{fast}}$ is the count rate of energetic positrons emitted from the $^{22}$Na source. The calculated efficiency is thus the total efficiency which includes the source construction, the geometric effect and the quality of the moderator. Before the measurements, the moderators would be subjected to chemical etching or thermal annealing. The chemical etching treatment was carried out by immersing the sample into chemical solution prepared by mixing 10 g NaOH, 10 ml ammonia (25–28%), 26 ml H$_2$O$_2$ (30%) and 54 ml distilled water. The annealing process was performed by electron beam heating in the vacuum of $2 \times 10^{-6}$ Pa. Details information concerning the beam design, experimental procedures and the data analysis could be found in [12,13].

3. Results and discussion

The positron emission efficiency of the 1 $\mu$m tungsten single crystal foil cleaned with acetone and annealed at 1600 °C for 20 min is shown by open circles in Fig. 1. From the figure, the count stays constant for $V_R$ smaller than about 24 V, decreases in the region $24 < V_R < 27$ V, and then reaches another constant count for $V_R > 27$ V.
This data can be understood from the relation between the longitudinal emitted positron energy $E_z$, and the potential barrier provided by the RFA [13,15,16]. Essentially for $V_R < 24$ V, all the emitted slow positrons are detected, while for $V_R > 27$ V, the slow positrons have been retarded leaving only unmoderated fast positrons. The difference between these two constant count regions gives the slow positron yield and the moderator fast to slow conversion efficiency was found to be $\varepsilon = 4.2 \pm 0.3 \times 10^{-4}$. The maximum emitted positron energy was observed to be $E = 2.8$ eV. The observed conversion efficiency is close to that reported by Lynn et al. [4] and Gramsch et al. [5]. If the tungsten single crystal foil was chemically etched before the annealing process, the positron emission efficiency was found to increase a little to $5.6 \times 10^{-4}$.

Using the same procedure we have also measured the slow positron emission efficiency of an inexpensive polycrystalline tungsten foil. A polycrystalline foil with a thickness of 15 µm and chemically etched for 9 min was observed to have the slow positron emission efficiency of $2.8 \times 10^{-4}$. Brusa et al. [14] electropolished polycrystalline W foil to the thicknesses of 4 and 6 µm and observed slow positron conversion efficiencies of $3.6 \times 10^{-4}$ and $2.0 \times 10^{-4}$, respectively, which are close to our observed value of the chemically etched polycrystalline W foil. In the present study, it was found that the polycrystalline W foil thickness became non-uniform after the etching and thus it was difficult to estimate its thickness.

The tungsten mesh moderators were cut from the tungsten mesh purchased from Swallow Metals and Components Ltd. The diameter of the wires was 20 µm and the mesh had a transmission efficiency of 92.5%. The mesh was folded into a number of layers with size 1 cm×1 cm and was fixed by spot welding. After cleaning the 12-folded W mesh sample with ultrasonic cleaner and acetone, the sample was chemically etched for 20 min. Slow positron emission measurement was performed on this sample and no slow positron emission was observed. This etched sample was then annealed at 1600 °C in vacuum for 20 min and a high value of emission efficiency ($1.2 \times 10^{-3}$) was achieved.

We have also studied the effect of the chemical etch duration on the slow positron emission efficiency of the 12-folded W mesh sample. The samples were subjected to chemically etching of 3, 5 and 8 min. The etched samples were then annealed at 1600 °C in vacuum for 20 min. The remaining wire diameters after these etching were estimated by measuring the differences of the sample masses before and after the etching and also by observation under an optical microscope. The wire diameters were found to be 16.5, 14.8 and 11.8 µm, respectively. The positron emission efficiencies were found to be $7.2 \times 10^{-4}$, $1.2 \times 10^{-3}$ and $7.9 \times 10^{-4}$, respectively. This implies the optimal efficiency can be achieved by under a 5 min chemical etch. The etching period dependence of the efficiency is unlikely to be related to the chemistry of the surface because etching for 3 min is sufficient to remove the surface of the moderator. The variations in efficiency result from changes in the mesh wire diameter as further elaborated in the coming paragraph.

The retarded field energy spectra $I(E_z)$ were also measured for the W mesh with different numbers of layers. These W mesh moderators were subjected to 5 min chemical etching and 1600 °C annealing before the positron emission experiments. The spectra for the 8-layer and the 12-layer mesh moderators are shown in Fig. 1. The difference in the integral count in the region $V_R < 24$ V is due to the difference in the fast to slow conversion...
efficiencies for the three moderators, for which
$\varepsilon(12\text{-layer W mesh}) > \varepsilon(8\text{-layer W mesh}) > \varepsilon(\text{W single crystal foil})$.

Fig. 2 shows the conversion efficiency and the maximum emitted positron energy as a function of the number of the mesh layer ($N_{\text{layer}}$). It is clearly seen from Fig. 2(a) that the conversion efficiency reaches its maximum at around $N_{\text{layer}} = 12$ with the high conversion efficiency of $1.2 \times 10^{-3}$. The optimal number of layers to achieve the maximum conversion efficiency observed in the present study is identical to that reported in the studies of Nagashima et al. [9] and Saito et al. [10]. The emitted positron energy was found to be independent of $N_{\text{layer}}$ with value of about $E = 3.1$ eV.

It would be interesting to investigate the physics behind the layer number dependence of the multi-layer W mesh moderator efficiency. Fast positrons implanted into the wires of the W mesh would lose energy to the W host. Fast positrons that penetrate a W wire will emerge and enter another W wire if their energy is still high. Since the W wire has diameter of 10–20 μm and the mean implantation depth is ~13 μm for fast positrons from $^{22}\text{Na}$ implanting into W, most of the positrons would survive no more than two implantations into the wires before they thermalize. This implies the effectiveness of thermalizing the fast positrons increases with the amount of W materials, i.e. the number of layers presented to the fast positrons. Once thermalized the positrons undergo diffusion and for those arriving at the surface, there is a finite probability of emitting into the vacuum. However, for the emitted slow positrons from the wire, they will annihilate if they knock on the W wires. This implies the W wires thus act as the screen for slow positron extraction and thus the efficiency decreases with the W wire density. This simple picture suggests a possible explanation for the number of folding layers dependence of the efficiency and also the existence of the ultimate number of folding layers for maximum conversion efficiency.

By considering the stopping of fast positrons and the screening of the emitted slow positrons by the mesh layers, we can derive the efficiency as a function of the number of layers. If, for simplicity, we assume all the fast positrons hitting on the W wire would thermalize, the probability for a fast positron being stopped at the $i$th layer is equal to:

$$P_{\text{stop};i} = t^{-1}(1 - t),$$

where $t$ is the transmission probability for a single layer. If the positrons stopped in the wire have a probability of $\mu$ of being re-emitted, then the probability for a fast positron to be stopped at the $i$th layer, finally passes through all the remaining layers and become usable slow positrons is equal to:

$$P_{\text{slow}} = P_{\text{stop};i}\mu^{N-i}.$$  \hspace{1cm} (1)

As we have totally $N$-layers, the total probability for extracting a slow positron is given by

$$P = \sum_{i=1}^{N} P_{i;\text{slow}} = \sum_{i=1}^{N} t^{-1}(1 - t)\mu^{N-i} = \sum_{i=1}^{N} \mu(1 - t)t^{N-1} = \mu(1 - t)Nt^{N-1}.$$  \hspace{1cm} (1)

For our present mesh with $t = 0.925$, the modeled efficiency as a function of the number of mesh layers is plotted in Fig. 2(a). Although the exact value $\mu$ in Eq. (1) is not known, the modeled curve was normalized with its function value at $N = 12$.
equal to that of the experimental value at $N = 12$. Despite of the precise prediction of the model that the maximum efficiency should occur at $N = 12$–14, the modeled curve shows a slowly varying efficiency with the mesh layer number, as contrast to the observed sharp peak at $N = 12$.

It is worth pointing out that the slow positron emission measurements as a function of the number of the mesh layers $N$ have been performed for two separate runs and the experimental data shown in Fig. 2(a) are the average values. It is because the measured emission efficiency is very sensitive to the source-moderator geometry and the observed data from a single run are possibly influenced by the slight difference of source-moderator geometry while installing each of the moderator samples. Nevertheless, the sharp peak observed at $N = 12$ in the present study and in [10] cannot be explained by the simple model considering the stopping of the fast positrons and the screening of the emitted slow positrons by the mesh layers and this requires further investigations in the future.

4. Conclusion

Fast to slow positron emission measurements were performed on W(001) single crystal foil, W polycrystalline foil and W mesh with different layers with slow to fast positron conversions of $4.2 \times 10^{-4}$, $2.8 \times 10^{-4}$ and $1.2 \times 10^{-3}$ being observed respectively. It is worth pointing out multi-folded W mesh has very good conversion efficiency. The conversion efficiency of the multi-folded W mesh moderator was found to depend on: (i) the annealing pretreatment, (ii) the diameter of the mesh wire (depends on the etching duration) and (iii) the number of the folding layers. For our W mesh with raw wire diameter of 20 μm and transmission efficiency of 92.5%, the optimal etching duration is 5 min and the optimal number of fold of 12.

Acknowledgements

This work was supported by the Research Grant Council, HKSAR (project nos.: 7107/02P and 7004/03P) and the CRCG, HKU.

References