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**LETTER TO THE EDITOR**

# Silicon carbide: a new positron moderator

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**Abstract.** Observation of copious positron re-emission from crystalline 6H-SiC, with no pre-treatment and without the need for ultra-high-vacuum conditions, suggests that this material may form the basis of an important new moderator for the production of monoenergetic positrons. Its positron work function is measured to be $-3.0 \pm 0.2$ eV. Its electrical characteristics point to SiC as a prime candidate for development as a field-assisted positron moderator, producing moderately intense slow-positron beams in laboratory-based systems and enabling a new generation of positron experimentation.

Slow-positron beams are being used today in an ever-increasing variety of fundamental and applied studies in atomic physics and condensed matter [1–3]. Such beams are created by exploiting the phenomenon of the re-emission of slow positrons from solids bombarded by fast positrons from a radioactive source, or created by pair production. A fraction of the implanted positrons diffuse to the exit surface of the material; they are then able to escape into the vacuum as long as there is no surface potential barrier to prevent them from doing so. In many materials the positron work function is negative, so that if the diffusing positrons are thermalized they are thrown from the surface with the same low energy. The efficiency $\epsilon$ of the moderator materials—defined as the number of slow positrons produced per fast primary positron—depends upon the magnitude of the positron diffusion or migration length compared to the mean implantation depth of the primary positrons, and the branching ratio for positron emission through the surface. $\epsilon$ has increased from $3 \times 10^{-8}$ in 1958 [4] to $7 \times 10^{-3}$ today [5]. The most successful, robust and widely used moderator has been well annealed tungsten [6], in both backscattering and transmission (thin film or mesh) geometry, with $\epsilon$ typically in the low to high $10^{-4}$ range, but the most efficient ($\epsilon \sim$ few $\times 10^{-3}$) moderators yet produced have been solid rare gas layers [7, 8]. This enormous increase in the efficiency for slow-positron beam production has led to a commensurate increase, both in number and diversity, of their applications in a wide range of scientific studies.

A number of intense positron beam facilities are in various stages of planning and implementation throughout the world [9]; the further advancement of positron beam spectroscopies in the laboratory, however, rests on the development of even higher-efficiency moderator materials. The most promising such advance is the field-assisted moderator (FAM), in which the fraction of implanted positrons reaching the surface is enhanced by

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an applied electric field which imparts to the positrons a drift velocity. This moderator scheme was first suggested in 1979 [10], and a decade later its fabrication from epitaxial metal-on-semiconductor systems was proposed [11, 12]. The most promising FAM materials to date have been Si–GaAs [13] and diamond [14], but the only successful experimental demonstration of FAM has been as a result of the surface charging of a rare gas moderator [15].

The current interest in SiC for use in high-temperature, high-power, high-frequency and radiation-resistant semiconductor device technology lies in its outstanding physical, chemical and electronic properties. In this letter we report the first promising experimental results obtained for this material which might serve as the basis for the future realization of a solid-state FAM device. Measurements on SiC were performed in the course of a comprehensive series of studies of the positron-related properties of carbides which had its origin in work on irradiation-induced precipitates in reactor steels [16]. During the course of slow-positron lifetime spectroscopy of ion-implanted 6H-SiC [17] a virgin (i.e. unirradiated) sample was used as a reference target. Evidence for copious slow-positron re-emission was observed; the nature of this re-emission was studied further by measuring directly the total re-emitted flux from a second piece of virgin SiC as a function of incident positron energy, and by measuring the longitudinal energy spectrum of the re-emitted positrons by a retarding field technique.

Lifetime spectra obtained for kiloelectron volt positrons implanted into single-crystal n-type 6H-SiC (0001 orientation, Si surface) [18] at the pulses positron beam facility in Munich [19] unexpectedly showed a strong side peak, especially for incident positron energies below a few kiloelectron volts. The shape of the side peak did not change significantly with incident energy, but its intensity decreased as the incident energy increased. Whereas small side peaks are inescapable in slow-positron lifetime spectroscopy, of height about three orders of magnitude smaller than that of the main (signal) peak, the ratio of the total main to side signal peak intensity shown in the spectrum in figure 1(a), for 1.5 keV positrons on SiC, is 0.86. It was also observed that the annihiliation signal count rate for positrons implanted at 1 keV was only about 65% of that measured at high energies. These observations were reproduced for a C-faced SiC wafer and, significantly, for synthetic diamond, which has been the subject of an earlier FAM study [14].

A number of systematic checks were carried out to determine whether or not the side peak could be due to backscattered positrons annihilating in view of the detector. The sample station in the pulsed positron beam system is surrounded by a large Faraday cage at the same potential as the target; this means that backscattered positrons should annihilate far away from the sample. This was confirmed by the disappearance of the side peak in the lifetime spectrum for SiC samples that had been (i) irradiated by 200 keV $Ge^+$ ions (fluence, $10^{19}$ $m^{-2}$), causing a highly defected subsurface region in which positrons are trapped and prevented from diffusing to the surface, and (ii) coated with a few nanometres of aluminium deposited by evaporation (figure 1(b)).

These checks, along with observations of the effects of varying the magnetic field and electrostatic potentials in the target region, led to the conclusion that the strong side peak is due to a weak potential gradient (of the order of a few hundred volts per metre) above the sample which directs slow re-emitted positrons back to the sample surface where they are annihilated. The most likely cause is the presence of insulator material close to the sample target. This explanation was given weight by performing the same measurement on polycrystalline tungsten, well annealed in ultra-high-vacuum conditions prior to installation in the pulsed beam system; tungsten is well known as an efficient emitter of work-function positrons. The resulting spectrum for W is shown in figure 1(c) and bears a striking

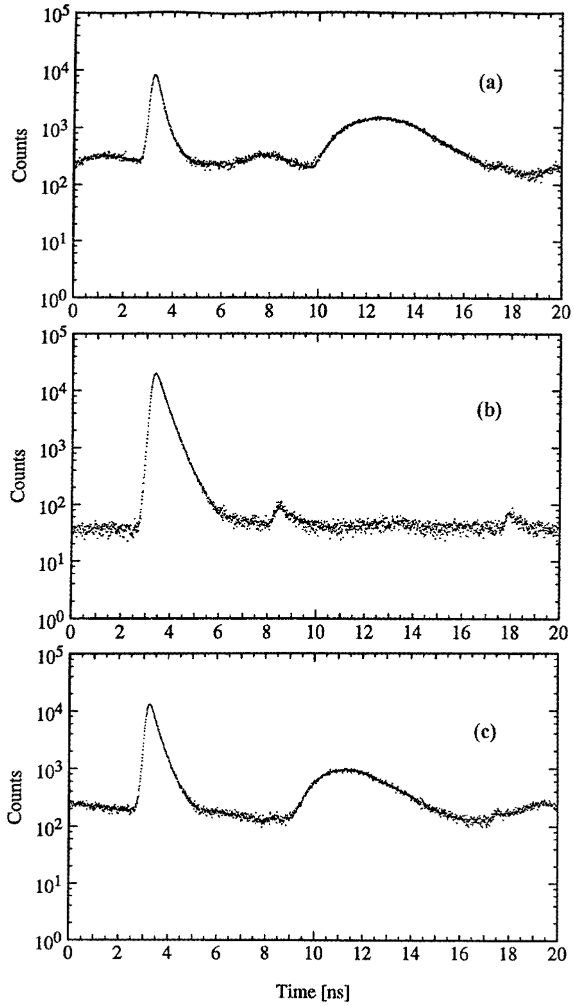


**Figure 1.** Positron time spectra measured at (a), (c) 1.5 eV and (b) 1.7 keV positron energy. The spectra are scaled to $10^6$ counts. (a) Virgin 6H-SiC (Si faced); the main to side peak intensity ratio (after background subtraction) is 0.86:1. (b) Virgin 6H-SiC (Si faced) coated with a few nanometres of aluminium deposited by evaporation; no intense side peak is visible. (c) Polycrystalline W foil which had been well annealed in UHV prior to loading into the measuring system; the main to side peak intensity ratio (after background subtraction) is 3.0:1.

resemblance to that for SiC.

The yield of slow positrons re-emitted from 6H-SiC (Si face, 0001 orientation) was measured using the UEA magnetic-transport positron beam [20]. A dc beam 4 mm in diameter and of controllable energy $E$ is transported to the sample, to which a bias potential $V_s$ is applied. Annihilation gamma rays from the sample are detected by a 72% efficiency Ge detector which views the sample through a 10 mm wide slit in a lead block, so that only annihilation events at the sample surface are observed [21]. Backscattered positrons are deflected by $\boldsymbol{E} \times \boldsymbol{B}$ plates mounted in front of the sample so that they cannot be reflected back on to the sample. Integral spectra of the type shown in figure 2 for

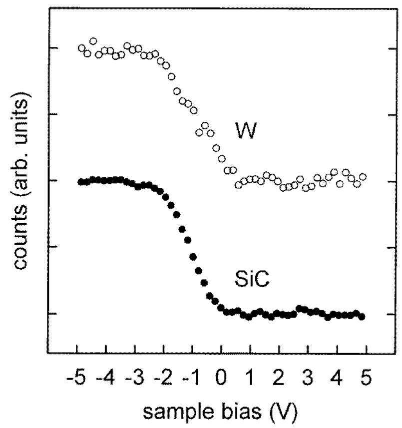


**Figure 2.** Integrated count rate profiles for SiC (incident positron energy $E = 1.4$ keV) (full circles) and annealed W (open circles).

SiC (reproduced for a number of specimens) and for annealed W were accumulated by recording the Ge detector pulse count rate (511 keV photopeak only) as $V_s$ was ramped from $-5$ to $+5$ V. The asymptotic count rate for $V_s = -25$ V was also measured and, after background subtraction, is proportional to the non-backscattered incident flux; the count rate for $V_s = +5$ V is proportional to the incident flux minus those positrons which are re-emitted at low ($\sim$eV) energies. In both cases the count rates include a contribution from short-lived para-positronium (p-Ps) which self-annihilates just above the surface (and hence in sight of the Ge detector). The $V_s = -25$ V measurement includes any epithermal positrons emitted at incident energies below 1 keV. If one assumes that the branching ratio for Ps formation is the same for both incident and returned slow positrons then these extra 'events' will increase both asymptotic count rates by the same fraction, and one can therefore (to first order) ignore their effect. The re-emitted positron fraction is therefore computed directly from the two count rates and is plotted in figure 3 as a function of incident positron energy. Also plotted is the result for ion-implanted (i.e., defected) SiC for comparison.

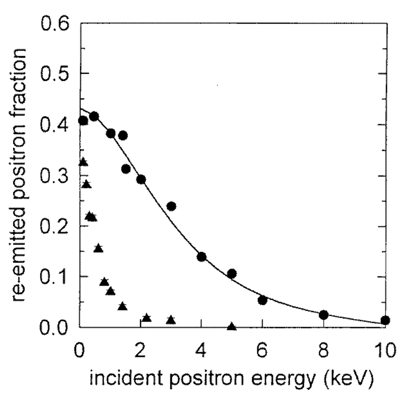


**Figure 3.** Re-emitted positron fractions as a function of incident positron energy: full circles, 6H-SiC; triangles, ion-implanted SiC. Solid line, implantation/diffusion model fit to SiC data, yielding a diffusion length of $70 \pm 10$ nm.

The persistence of positron re-emission from the virgin SiC to energies of several kiloelectron volts is characteristic of work-function emission [22]; this statement is supported by the much more rapid decrease in the emission of positrons from defected SiC, which is the signature of epithermal positron emission [23] and which is almost identical to that seen for silicon (which has a positive positron work function). The fit to the data shown in figure 3 assumes a Gaussian derivative implantation profile, and yields an effective diffusion length for thermalized positrons in SiC of $70 \pm 10$ nm, in qualitative agreement with energy-dependent Doppler broadening measurements on the same sample performed by the present authors. The zero-energy fraction of approximately 40% competes very well with that reported for commonly used moderator materials.

By examining integral spectral such as those in figure 2 for incident energies between 1 and 10 keV one can estimate the maximum energy of the re-emitted positrons and, hence, the positron work function $\phi_+$, of the SiC surface. (Below 1 keV evidence of (higher-energy) epithermal positron emission is seen in the integral spectra; measurements by the present authors on Si and many other materials suggest that above 1 keV incident positron energy any re-emission is dominated by the work-function process.) By this method one arrives at a value of $\phi_+ = -3.0 \pm 0.2$ eV, which is essentially the same as that deduced for annealed tungsten; the similarity between the two spectra in figure 2 is apparent even by eye. This relatively high work-function value is, as in the case of tungsten, consistent with efficient slow-positron re-emission (even from contaminated, or uncleaned, surfaces). LMTO–ASA calculations of the positron affinity [24], combined with the results of electron work-function measurements [25], suggest that $\phi_+$ for SiC is $\sim -1.0$ eV; the discrepancy between this and the apparent experimental result may be resolved by further measurements on atomically clean SiC surfaces, and/or on further refinements to the theoretical treatment (including the investigation of different prototypes); however, it is encouraging that both experiment and theory predict a relatively large negative work function for SiC.

It is important to consider SiC as a candidate for primary positron moderation (rather than the remoderation successfully demonstrated above) and as a candidate for field-assisted moderation and remoderation. Firstly, without field assistance, a primary moderation efficiency $\epsilon$ of $\sim 1.5 \times 10^{-3}$ may be estimated using the method of Mills [26] by using the diffusion length of 70 nm deduced above. This is not as high as the figure for annealed W, primarily because of the lower density of SiC, but it should be remembered that SiC, unlike W, does not require careful annealing in high or ultra-high vacuum, and that no surface preparation is required. Reasons for this probably include the low concentration of positron trapping sites in as-grown SiC, and the relatively high work function; the latter makes re-emission from SiC insensitive to any surface contamination. Although a systematic series of comparative tests of re-emission from SiC surfaces with different treatment histories has yet to be made, no differences were seen in its re-emission properties in UHV and non-UHV conditions. Steps to fabricate a thin, transmission-geometry SiC primary moderator are in progress.

More hopeful is the possibility that SiC may form the basis of the first effective FAM device, for both primary moderation and re-moderation. Using data supplied by the manufacturers [18] and with reference to the work of Beling *et al* [12] it is estimated that a potential difference of the order of a kilovolt across a SiC wafer thinned to a few tens of micrometres in thickness would enhance slow-positron emission by the orders of magnitude hoped for in FAM moderators. Practical problems associated with electrical contacts have been tackled for a number of years [13, 27] and it is the authors' opinion that these problems will be solved in the near future. Cooling the moderator to temperatures at which the positron mobility is significantly increased would improve the performance, either by increasing the emitted flux or allowing the use of lower electric fields/thicker wafers.

In conclusion, SiC has the potential for development as a robust and efficient positron moderator. More significantly, however, it offers the real possibility for development as a field-assisted moderator, allowing the production of moderately intense positron beams in laboratory-based systems and opening the door to a new generation of positron experiments [28].

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