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LETTER TO THE EDITOR

Positron diffusion in an electric field in Si

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Abstract. Positron diffusion in an electric field has been experimentally investigated by implanting positrons in the depleted zone of an Au/Si Schottky diode. The results show that fields with an intensity of about 10^4 V cm^{-1} have a strong effect on positron diffusion. Before annihilation, thermalised positrons can drift distances of about 2 μm.

Positron annihilation in thin films and near-surface layers of solids is being increasingly investigated, because of the progress in the production of monoenergetic beams of low-energy (0–30 eV) positrons (Schultz and Lynn 1988 and references therein). For implantation depths below a few thousand angströms, it has been observed that positron annihilation characteristics are strongly affected by the positron incident energy. The region where positron–electron annihilation occurs depends on positron diffusion. Positrons may annihilate in the bulk, be trapped at bulk defects, or, when implanted in the near-surface layers, diffuse at the solid surface and annihilate there (Schultz and Lynn 1988 and references therein). The annihilation characteristics at the surface usually differ much from those in bulk. Consequently, the annihilation characteristics of low-energy positrons vary with the probability that they again reach the surface through which they have been implanted. This variation is reflected by the dependence of the annihilation characteristics on the incident energy of the positrons. A study of this dependence provides a direct way to measure positron diffusion in a defect-free solid (Schultz and Lynn 1988 and references therein).

Positron diffusion in metals and semiconductors has been determined experimentally by this method in several recent studies due to the advance in positron beam technique (Schultz and Lynn 1988 and references therein). When applied to metals with a proper analysis of the annihilation data, this method gives consistent results on positron diffusion constant D_+ and positron diffusion length l_+ ($l_+ = (D_+\tau)^{1/2}$ where τ is the positron lifetime in defect-free bulk) (Huomo *et al* 1987, Soininen *et al* 1989). In semiconductors, the results show a large dispersion. In Si, the positron diffusion length varies from 1000 to 2400 Å and shows an unexpected dependence on the doping and heat treatments (Mills and Murray 1980, Nielsen *et al* 1985, 1987, Schultz *et al* 1988, Keinonen *et al* 1988). In semiconductors, positron diffusion may be strongly affected by an electric field existing in near-surface layers due to surface charge. Uedono *et al* (1989) have recently reported results showing that annihilation characteristics change with the bias voltage

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applied to a Si/SiO$_2$/Si system. However, as the electric fields have been unknown in most experiments performed in semiconductors, the annihilation data have been analysed without taking into account the effect of the electric field. Such an analysis only yields the effective positron diffusion constants and lengths, which may explain the large dispersion of the results.

In order to investigate the electric-field effects on positron diffusion in controlled conditions we have performed positron beam experiments in a Au/Si Schottky diode. Positrons were implanted in the depleted zone of the Schottky diode biased under various conditions. This Letter reports preliminary results, which clearly demonstrate the strong effects of the electric field on positron thermal motion. In the field, the effective positron diffusion length prior to annihilation can be enhanced by an order of magnitude and reaches up to 2 μm.

We have used a Schottky barrier diode prepared on a P-doped n-Si crystal cut from a Czochralski-grown wafer with electron concentration of 7.4×10^{14} cm^{-3} at 300 K. The diode used for positron experiments was fabricated by evaporation of a gold layer of thickness about 100 Å through a mask of 8 mm diameter onto the n-Si crystal. Additional diodes of 1 mm diameter were prepared for capacitance–voltage measurements. The ohmic contacts were formed on the back of the n-Si crystals by deposition of metallic gallium. The Schottky structure of each diode was checked for satisfactory forward and reverse current–voltage characteristics. The carrier concentration of 7.4×10^{14} cm^{-3} was determined from capacitance–voltage measurements performed on the 1 mm diodes. The Schottky barrier height for electrons at zero bias was determined to be 0.83 V from the capacitance–voltage measurements. These values are used to calculate the electric field and the width of the depleted layer in Si as a function of the bias voltage applied to the diode. The field is calculated in the abrupt approximation where the charge space in Si is described by a step function of width equal to the depletion layer. The field is maximum at the Au/Si interface and decreases linearly to zero at the end of the depleted zone.

The diode was mounted in the metallic sample holder of the positron beam facility at the Helsinki University of Technology (Lahtinen *et al* 1986). It was checked that the current–voltage characteristics of the diode *in situ* under ultra-high vacuum were similar to the curves obtained before mounting. Positron annihilation under various bias conditions was studied by recording the Doppler broadening of the 511 keV annihilation ray. The annihilation lineshape was characterised by the so-called S-parameter, defined as the relative area of the central region, 511 ± 1 keV, of the 511 keV annihilation ray (Schultz and Lynn 1988). The S-parameter represents the fraction of positron–electron pairs with a momentum component in the range 0 ± 0.5367 au. This fraction varies with the region and the state from which positron annihilation occurs. Two types of runs were performed. First, the energy of the positron beam was fixed and the bias voltage of the diode was varied from reverse bias of -5.5 V to forward bias of 0.45 V. Secondly, the bias voltage of the diode was fixed and the positron incident energy was varied from 0 to 28 keV.

Figure 1 shows the S-parameter as a function of the bias voltage V_b for a positron energy of 10 keV. This energy corresponds to a mean implantation depth of 0.7 μm in Si as calculated from the positron stopping power. One can clearly see that the S-parameter changes as the diode bias is varied from -5.5 eV to 0.5 eV. The variation of the S-parameter as a function of bias reflects that the S-parameter is a superposition of annihilation occurring from different regions or positron states. For all the bias voltages, the field is directed towards the Au/Si interface. The field intensity decreases as the

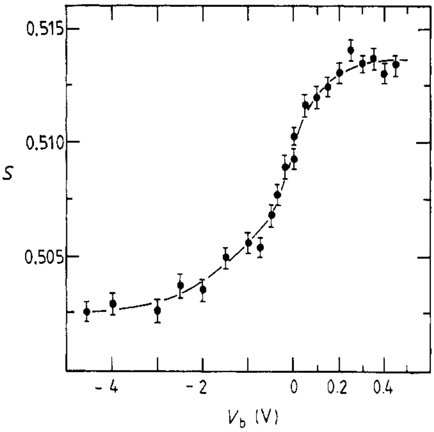

Figure 1. Annihilation lineshape parameter S as a function of applied voltage V_b at the Au/Si Schottky diode. The positrons have a fixed incident energy of 10 keV. The full curve is a guide for the eye. The lineshape S-parameter is the fraction of electron–positron pairs with a momentum component in the range 0 ± 0.5367 au.

voltage increases from -5.5 eV to 0.5 eV. For high reverse bias ($V < 0$), the positrons implanted in Si are strongly repelled towards the Au layer and the fraction of positrons annihilating at the Au/Si interface increases. For forward bias ($V > 0$), fewer positrons are able to reach the Au/Si interface and the fraction of annihilation occurring in the bulk increases. It can be concluded from figure 1 that the $S_{Au/Si}$-parameter is lower than the S_{Si}-parameter.

In figure 1, we can also observe two important bias regions, $V > 0.3$ eV and $V < -4$ eV, where the S-parameter reaches a constant value. In the first one ($V > 0.3$ V) the positron diffusion is practically free from field effects. In the second one ($V < -3$ V) the field effect on positron motion appears to be saturated. The first region means that the zero-field condition for positron motion is already reached at $V_b = 0.3$ V. At this bias, the maximum field is 7×10^3 V cm^{-1} and the depletion layer has a width of 0.62 μm. This depletion width is comparable to the 0.7 μm mean implantation depth of the 10 keV positrons. In the second region, the saturation in the field effect is obtained at $V_b = -3$ V, corresponding to a maximum field of 2.7×10^4 V cm^{-1} and a depletion layer width of 4.3 μm. A field of this magnitude is sufficient to sweep all the positrons implanted at 10 keV back to the Au/Si interface.

Figure 2 presents the S-parameter as a function of positron energy E_+ for various bias values. Clearly, these curves show two parts. In the first part, for incident energy below 3 keV, the S-parameter is insensitive to the applied voltage. In the second part, for incident energy above 3 keV, the S-parameter is strongly affected by the bias voltage. This separation is easily understood. The first part corresponds to positrons implanted in the 100 Å Au layer and the second part to positrons implanted in the space-charge layer in Si. The curves obtained at forward bias $V_b \geqslant 0.35$ eV become similar, which confirms that at these bias voltages the field is too low to affect positrons.

The S-parameter in the energy region $E_+ \leqslant 3$ keV corresponds to positrons implanted in the Au layer and diffusing to the vacuum/Au interface or to the Au/Si interface. The peak at 2 keV is due to positronium formation at the vacuum/Au interface. The annihilation parameter at the Au/Si interface denoted by S_{Au} in figure 2 is well

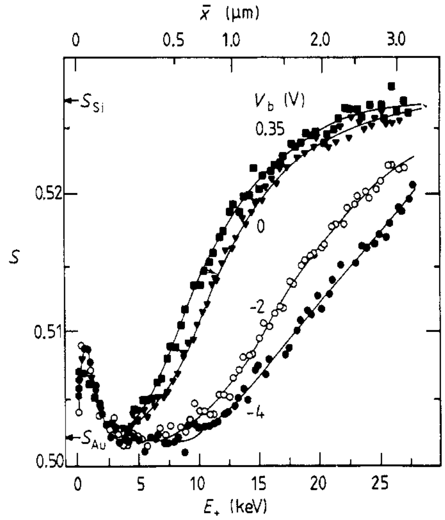

Figure 2. Annihilation lineshape parameter S as a function of positron incident energy for various bias voltages of the Au/Si Schottky diode. The mean implantation depth, $\bar{x}$, corresponding to the positron incident energy is also given. Forward bias is positive and reverse bias is negative. The full curves are a guide for the eye.

defined by the plateau in the curves for $V_b = -2$ V and -4 V. It corresponds to the value 0.5020. For $V_b = -4$ V, all positrons implanted with $E_+ \leq 10$ keV diffuse back to the Au/Si interface as already concluded from figure 1. The S-parameter for forward bias $V_b \geq 0$ V at high energies $E_+ > 25$ keV tends to reach a saturation at $S_{Si} = 0.5270$. This regime of saturation represents the situation where all positrons annihilate in Si before reaching the Au/Si interface.

The value of S equal to $(S_{Au} + S_{Si})/2$, $S = 0.5150$, represents the situation where 50% of positrons diffuse to the Au/Si interface after implantation. This value is reached by positrons of 10 keV incident energy in zero field ($V_b \geq 0.35$ V) and by positrons of 23 keV in high field ($V_b \geq -4$ V). For positrons of 23 keV, the mean implantation depth is 2.5 μm. At $V_b = -4$ V, the maximum field is 3.2×10^4 V cm^{-1} and the depletion layer has a width of 2.8 μm. The average field from 0 to 2.8 μm is 1.6×10^4 V. This field is able to make positrons drift over about 2 μm during their mean lifetime of 220 ps. From these numbers, we can calculate a rough estimate for positron mobility $\mu_+ \sim 50$ cm^2 V^{-1} s^{-1} at 300 K. Mills and Pfeiffer (1977) have made a direct mobility measurement in a Si(Li) gamma detector and their low-temperature results extrapolated to 300 K give 70 ± 10 cm^2 V^{-1} s^{-1}, in reasonable agreement with the order of magnitude we have found.

In conclusion, by implanting positrons in the depleted zone of a Au/Si Schottky diode, we have demonstrated experimentally that electric fields of order 10^4 V cm^{-1} have strong effects on positron diffusion. Under a field of this magnitude, positrons can drift distances up to a few μm before annihilation.

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