Variable low energy positron beams for depth resolved defect spectroscopy in thin film structures

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The design, development and commissioning details of an ultra high vacuum compatible, magnetically-guided and compact variable low energy positron beam facility are reported. Information pertaining to the nature, concentration and spatial distribution of defects present at various depths in the near-surface layers of a material can be obtained using this technique. Some of the experimental results obtained using this facility, in terms of surface-sensitive positronium fraction measurements on Cu surfaces as well as defect-sensitive Doppler broadening measurements on semiconductor interfaces and ion irradiated silicon are presented. These results essentially provide an illustration of the research capability of the technique for the study of sub-surface regions and thin film interfaces.

POSITRON annihilation spectroscopy (PAS) is a powerful and versatile tool for materials science studies[1]. In PAS techniques, positrons from a radioactive source are used as a probe for the medium under study. Positrons injected into the sample get thermalized and annihilate with electrons of the medium, giving rise to annihilation gamma rays. The information pertaining to the electron momentum distribution and local electron density of the medium under study can be obtained using PAS. It has been widely used, over the last several years, for a variety of problems[2], addressed to the study of electronic structure and atomic scale defect properties in metals, alloys, semiconductors, superconductors, nanophase materials and quasi-crystals. Defect concentration ranging from 10^{-7} to 10^{-4} can be probed using PAS techniques, which have high sensitivity and selectivity to open volume defects in materials. However, owing to the continuous energy distribution of positrons emanating from a radioactive source, with the end point energy in MeV region, the technique provides information about the bulk state of the material, averaged over depths starting from the surface to several microns inside. Thus, atomic layers at a specific depth cannot be selectively probed by conventional PAS experiments.

Knowledge of the defect structures and their depth distribution in sub-surface regions of materials, thin films, epilayers and interfaces is essential to our understanding of the characteristics and behaviour of many modern materials which are of technological importance. The emergence of variable low energy positron beams[3-6] (LEPB) in the energy range of a few eV to several keV has come to fulfill this need quite admirably, through its capability of selective depth profiling of defects. In LEPB, a fraction of positrons from a primary radioactive source is thermalized and reemitted as thermal positrons using a moderator, thereby giving rise to a secondary source of monoenergetic positrons. These can be focused, transported and accelerated to the desired energy to form a monoenergetic positron beam of variable low energy. Since the positron implantation depth has a power law dependence[3] on beam energy, fixing the latter ensures depth selectivity. The defect-sensitivity coupled with the depth resolved capability of LEPB facilitates unique means of characterization of defects in thin-layered structures. For example, a detailed characterization of defects at surfaces and buried interfaces, which is very vital and important to semiconductor industry, can be carried out in an elegant and nondestructive way using LEPB. This technique can provide defect specific information, complementary to other experimental techniques such as Auger Electron Spectroscopy (AES) and Secondary Ion Mass Spectrometry (SIMS), which are useful in giving depth resolved information about composition and chemical impurities in the material.

In this account, the details of development, commissioning and operation of an LEPB facility in our laboratory and the results of initial research carried out using the facility are reported. This is the first facility of its kind operating in India. The organization of the paper is as follows. The first section deals with (a) the basic concepts involved in positron beam production (b) the details of design and commissioning of the facility, and (c) the details of the experimental set up and the automation of experimental data acquisition. The experimental results in terms of positronium fraction measurements on different Cu surfaces and depth resolved Doppler broadening measurements on oxide-semiconductor interfaces and Ar ion-induced defects in

Si are discussed later. Finally, summary and conclusions are highlighted.

Experimental details

Basic concepts in beam production

The production of low energy positron beam comprises of four main steps, viz. (i) monoenergetic slow positron production which involves a combination of a primary source and a moderator in an appropriate geometry. Extraction and focusing of slow positrons from the moderator surface using necessary lens arrangement. (ii) Energy or velocity discrimination to eliminate the non-thermalized fast positrons. (iii) Transport of the slow positron beam up to the target, and (iv) Acceleration of slow positron beam to define the chosen beam energy.

Slow positron production. Some of the radioactive sources[2] used for conventional PAS measurements are ^{22}Na, ^{58}Co and ^{64}Cu. Among these, ^{22}Na has been the most popular choice owing to its long half-life (2.6 yrs) coupled with the commercial availability of carrier-free ^{22}NaCl with high positron activity. In most of the laboratory-based beams, source strengths of the order of 50 mCi are used to obtain a primary positron intensity of about 10^9 s^{-1}.

Moderator is the most crucial component in the production of slow positron beams. When a moderator foil is exposed to a radioactive source such as ^{22}Na, a small fraction of energetic positrons from the β^+ spectrum gets thermalized inside the moderator foil and diffuse to the surface within its lifetime. A key property[3,4] that is exploited is the positron negative work function Φ^+ for some of the metallic surfaces, which results in spontaneous reemission of slow positrons. Certain oriented faces of crystalline Ni, Mo and W exhibit negative Φ^+ and hence can be used as positron moderators. Moderation efficiency ε is defined as the ratio of the number of slow positrons emitted by a moderator to the number of fast positrons emanating from the radioactive source. The value of ε ranges from 10^{-3} for cooled solid inert gas moderators to 10^{-4} or 10^{-5} for metallic moderator foils[3,4]. Among all the metallic moderators, single crystalline W(100) foil is widely used in the production of laboratory beams, owing to its satisfactory moderation efficiency and long-term stability in slow positron yield. The re-emitted slow positrons from the moderator surface are monoenergetic with the longitudinal energy equal to the Φ^+ value. Also, the transverse energy spread, which gives rise to the angular distribution of slow positrons, is small and favourable[4] for the extraction of a well-focused positron beam by using appropriately designed beam optics.

Various source-moderator geometries[3,4,6], viz. reflection-mode, back scattering and transmission mode are normally used for the generation of slow positrons from the moderator. Due to the availability of self-supporting films of typically 1 μm thick metallic moderators, the transmission mode geometry has gained popularity. In this arrangement, the fast positrons from a source impinge on one surface of the moderator film, while the slow positrons reemitted from the other surface of the moderator, are extracted to form the slow positron beam. Taking into account the typical source strengths, source-moderator geometry and the optimal moderation efficiency, a slow positron beam intensity of about 10^4 to 10^5 s^{-1} is achieved in most of the laboratory beams[3].

Energy discrimination. The slow positrons emanating from the source-moderator geometry are mixed up with the fast component of unmoderated β^+ positrons. Thus, it is necessary to eliminate the fast positron background and preserve only the slow positrons for beam transport. This energy (velocity) discrimination can be accomplished in different ways. By employing (i) perpendicular electric (**E**) and magnetic (**B**) fields, known as **E** × **B** filter or (ii) parallel plate electrostatic analyser known as electrostatic mirror or (iii) radially bent magnetic field known as **R** × **B** filter, where **R** is the radius of curvature and **B** is the magnetic field. By passing through any of these devices, slow positrons of well defined energy will get transmitted, while the fast positrons are eliminated. Based on the nature of beam transport, viz. electrostatic or magnetic, any one of the above methods can be employed to selectively filter the slow positron beam.

Beam transport. Slow positrons emanating from the moderator can be transported to the target region by employing either electrostatic fields or by magnetic fields. In the former case, a series of electrostatic lenses of optimized separations and voltages are so arranged as to transport the beam up to the target. The beam characteristics in terms of its size and divergence can be controlled in electrostatic beam transport. However, due to various lens elements involved, the optimization of beam transport is rather involved. In the case of magnetic beam transport, an axial guiding magnetic field is applied in the direction of propagation of slow positrons. This confines the divergence of the beam and transports the individual slow positrons in helical paths along the direction of magnetic field. This guiding magnetic field can be applied either by using solenoidal coils or Helmholtz coils depending upon the geometry of the beam line.

Acceleration. The positron beam can be accelerated in two ways. In the first scheme, the source-end is floated at the required positive voltage and the target is grounded.

In the second method, a small kinetic energy is imparted to slow positrons for transport and the beam is accelerated to the desired energy finally at the target. In the later scheme of post-transport acceleration, the target is suitably biased at a negative high voltage with respect to the beam line. Based on the design and construction, both modes of acceleration are in use. The depth to which the positrons get implanted is determined by the acceleration imparted to the positron beam, viz. the positron beam energy. The mean depth of positrons Z (in nm), measured from the surface through which positrons enter the solid, is related to the incident positron energy E_p (in keV), by the empirical relationship[3], $Z = 40E_p^{1.6}/\rho$, where ρ is the density of the material in g/cm^3. Thus, the incident positron beam energy can be varied to obtain a depth-resolved annihilation signal.

Design details of LEPB

A cross-sectional view of the LEPB facility[7,8] in our laboratory is shown in Figure 1 with relevant details of automation (automation details are discussed separately in the subsequent section). The ultra high vacuum (UHV) compatible LEPB system consists of three inter-connected main parts, viz. a source chamber, a U-shaped beam transport section and a target chamber.

The source chamber houses the primary positron source, moderator foil assembly and the electrostatic lens system. The primary positron source is a 50 mCi ^{22}Na source of 3 mm diameter mounted on a linear drive mechanism. The moderator foil is a single crystal W(100) of 1 μm thickness and 6 mm diameter. The moderator is mounted in a transmission geometry and the source-to-moderator separation is adjustable to within 1 mm. The source chamber is pumped using an ion pump of 60 l s^{-1} capacity.

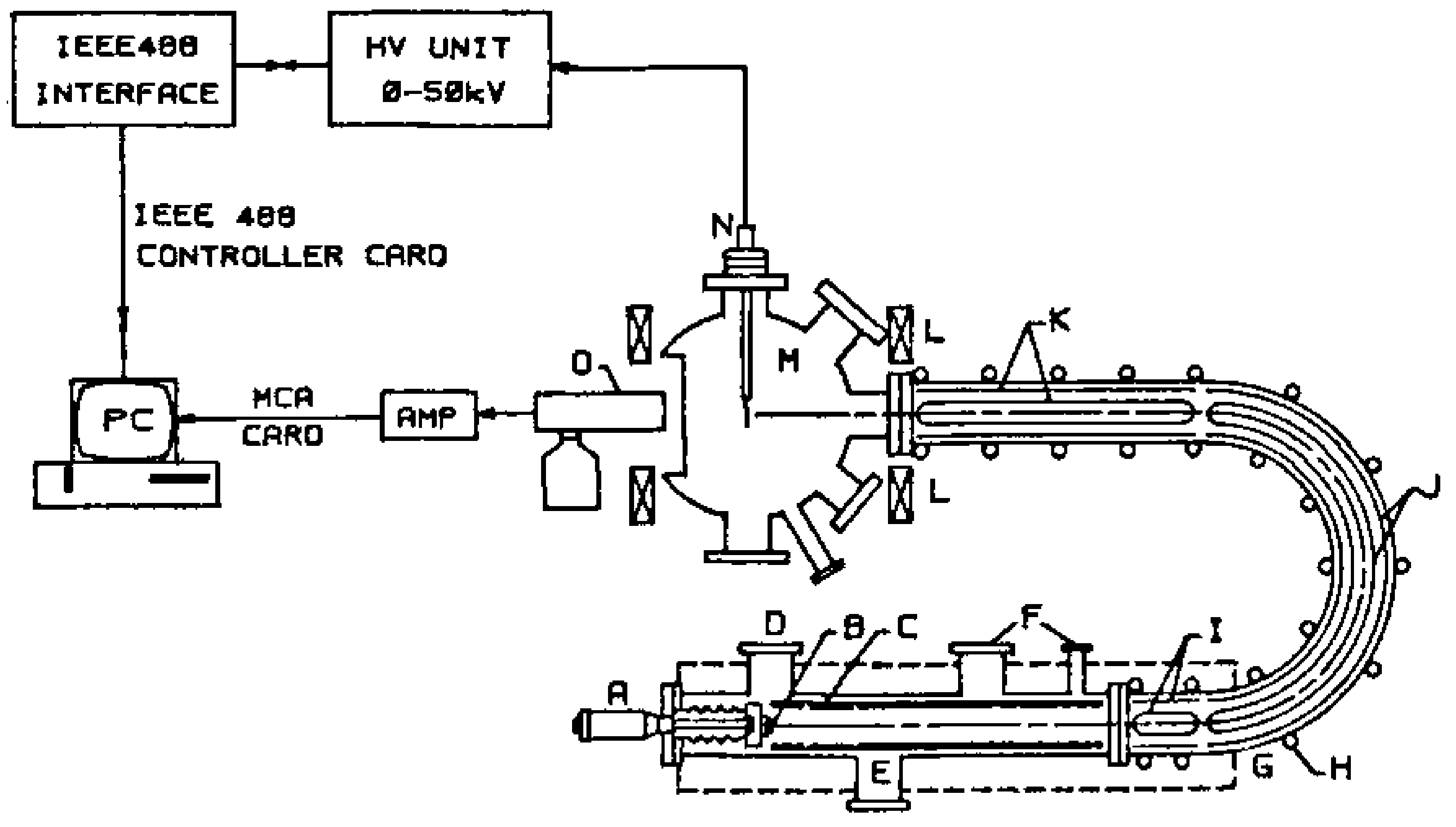

Figure 1. A cross-sectional view of the variable low energy positron beam system shown with constituent parts and the automation details. A, Source mounted on a linear drive; B, Moderator foil; C, Electrostatic lens assembly; D and E, Port for vacuum monitoring and pumping; F, Port for lens voltage feedthrough; G, Radiation shield; H, Solenoidal guiding magnetic field; I and K, Steering coils at the entrance and exit; J, Orthogonal drift correction coils; L, Helmholtz coils; M, Target chamber; N, High voltage feedthrough cum sample holder; O, Detector.

Electrostatic lens system for slow positron extraction and focusing has been designed, based on an electrostatic beam optics program developed[9] in-house. A transfer-matrix method[10], coupled with the documented data on the focal properties of commonly used electrostatic lenses has been used in the simulation of beam trajectories. Taking into account the separation between object (moderator foil) plane and image plane (aperture located at the entrance of U-tube) and required beam characteristics, a combination of an asymmetric einzel lens (AEL) and a two-tube lens (TTL) has been found to be the optimum choice. Accordingly, the separation and voltages of the lens elements have been fixed. The calculated positron trajectories from the moderator to the aperture are shown in Figure 2. The slow positron beam from the moderator, with a diameter of 6 mm and divergence of ±10°, is extracted by the lens assembly and focused on to the aperture to form a beam of about 2.5 mm in diameter and divergence of ±1°. This is achieved by imparting an accelerating voltage of 225 V to the slow positrons re-emitted from the moderator surface. This transport energy is found satisfactory for beam transmission from the production point to the target chamber.

The U-shaped beam transport system has an aperture at its entrance, into which the slow positron beam is focused by the lens assembly. The guiding magnetic field is generated by doubly wound solenoidal coils on the U-tube. The strength of the guiding magnetic field is 7 mT, corresponding to which the positrons injected with an energy of 225 eV spiral along the guide tube with a radius of gyration of less than 1 mm. The U-shaped magnetic bend, which is similar to the one reported earlier[11] has two-fold functions: (i) It eliminates the fast positrons and selectively transports slow positrons based on the principle of **R** × **B** filter. (ii) It prevents direct line of sight between the source and the detector positioned at the end of the transport tube. Slow positrons

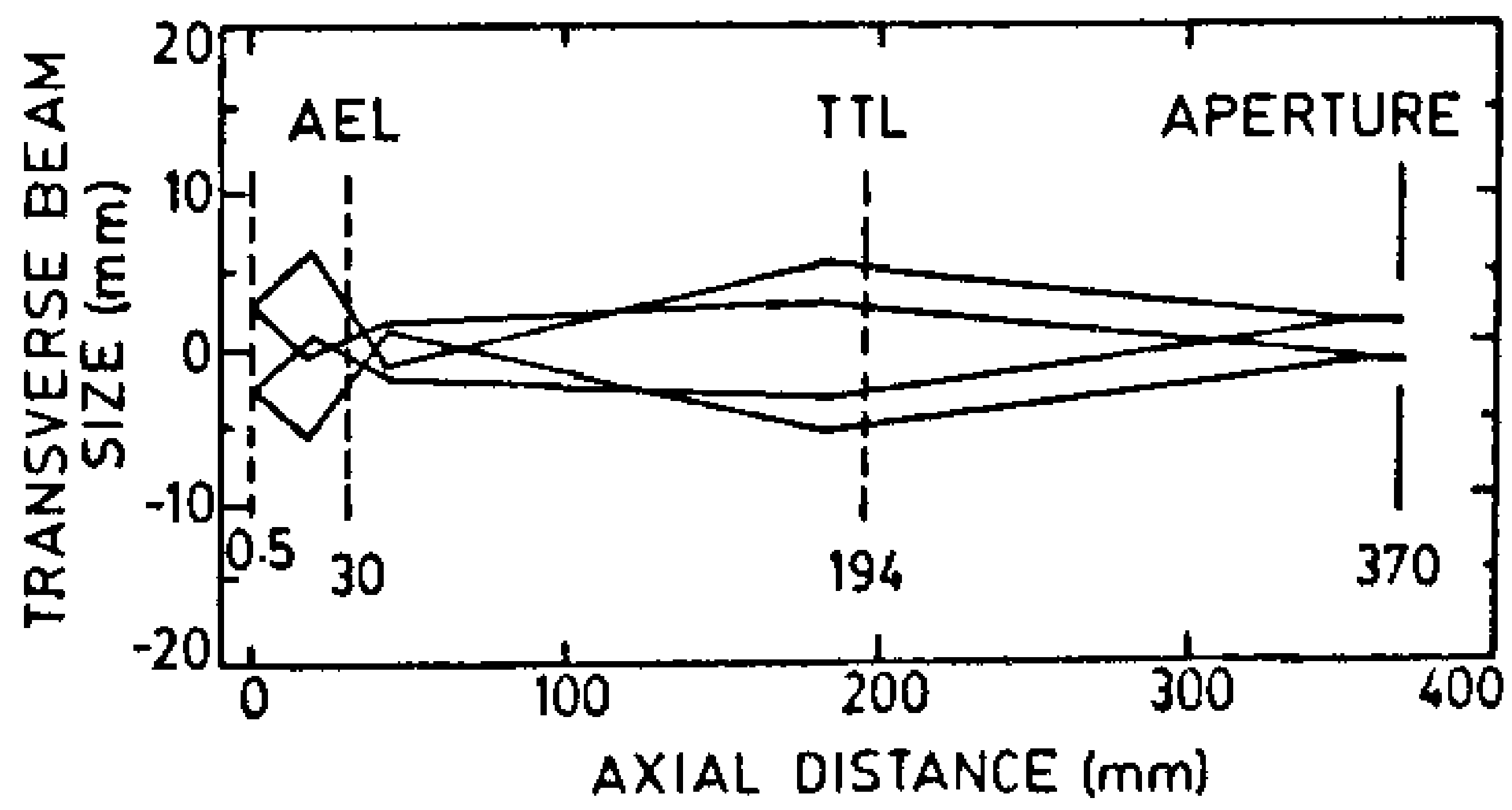

Figure 2. Calculated positron beam trajectories with rays traced from the moderator to the aperture, located at the entrance of U-shaped transport tube. The positions of the moderator, AEL, TTL and aperture are marked in the figure.

of chosen energy, while negotiating the curved portion of the U-bend, experience a drift away from the center. The drift compensation is achieved by two pairs of orthogonally placed correction coils positioned on the curved portion of the U-tube. These coils generate the required transverse magnetic fields to deflect the beam on to the central axis of the beam tube. Apart from these drift compensation coils, another two pairs of steering coils rotated by 90° are placed on the entrance and exit portions of the U-tube to take care of the lateral shifts in beam positions. The typical value of magnetic fields generated by the correction coils is 0.1 mT.

The slow positron beam is finally transported into a target chamber. This houses the sample under study, which is mounted on the tip of an UHV compatible high voltage feedthrough. The sample can be biased at any required negative high voltage from 0 to 50 kV, to define the positron beam energy. In view of the connecting flange between the U-tube and the target chamber and the irregular geometry of the target chamber, the axial magnetic field has been extended beyond the sample region using a pair of Helmholtz coils. This magnetic confinement in the target chamber eliminates beam divergence while the beam is hitting the sample. The detection of slow positron-induced annihilation gamma-ray is carried out using either a $3'' \times 3''$ NaI detector or an intrinsic germanium detector, which is positioned outside the target chamber in close proximity to the sample. The target chamber is pumped using a $500\,\mathrm{l\,s^{-1}}$ turbo pump.

In view of the high source strength of ^{22}Na, the source-side of the beam line has been shielded with interlocking gap-free lead blocks arranged in modular units. The detector is also appropriately shielded with lead bricks to minimize the gamma ray background. The radiation-shielding assembly on the source side has been designed, with provision for easy access to the moderator as well as for the retraction of the source flange during beam diagnostic operations. The whole beam line has been wound with heater wires so as to bake the complete system at a temperature of ~200°C for UHV operations. An ultimate vacuum of 3×10^{-8} mbar has been obtained in the beam line as well as in the target chamber.

Commissioning and beam tuning details

Having integrated the whole beam system, the crucial step involved in commissioning the beam is the high-temperature annealing treatment of the W(100) moderator foil. W(100) foil in the as-received condition, does not show any measurable slow positron yield. The presence of impurities such as carbon and surface defects need to be removed by high temperature annealing treatment. The 1 μm thin W(100) foil, is sandwiched between 150 μm thick W supporting foils and has been subjected to thermal annealing treatment at ≈ 2400 K in repeated cycles in high vacuum to obtain an optimum slow positron yield, based on an earlier study[12]. This moderator foil after high temperature treatment, has been mounted in the beam line using a stainless steel assembly, which is in axial alignment with the source capsule.

There are 15 beam transport parameters to be critically tuned and optimized to obtain beam transmission from the source chamber to the target. Each of these parameters is sequentially optimized starting from the source side to the target side. A $3'' \times 3''$ NaI detector has been used at the target chamber for the detection of 511 keV annihilation gamma rays due to slow positrons striking the target. Figure 3 shows the complete energy spectrum of the gamma rays obtained from the NaI detector. When the beam transport is not activated, only the background counts are observed. When the slow positron beam transport is switched on, the dominant 511 keV gamma ray photo peak is observed. This marks the successful transport of slow positrons into the target chamber and proves that the beam is striking the target. The effect of various transport parameters on the beam transmission has been studied. In beam diagnostic runs, when any of the beam transport sub-systems is switched off, the gated 511 keV gamma ray counts at the target drops down to the background counts. This indicates the successful functioning of various in-house developed electrostatic and magnetic transport sub-systems and the complete beam system.

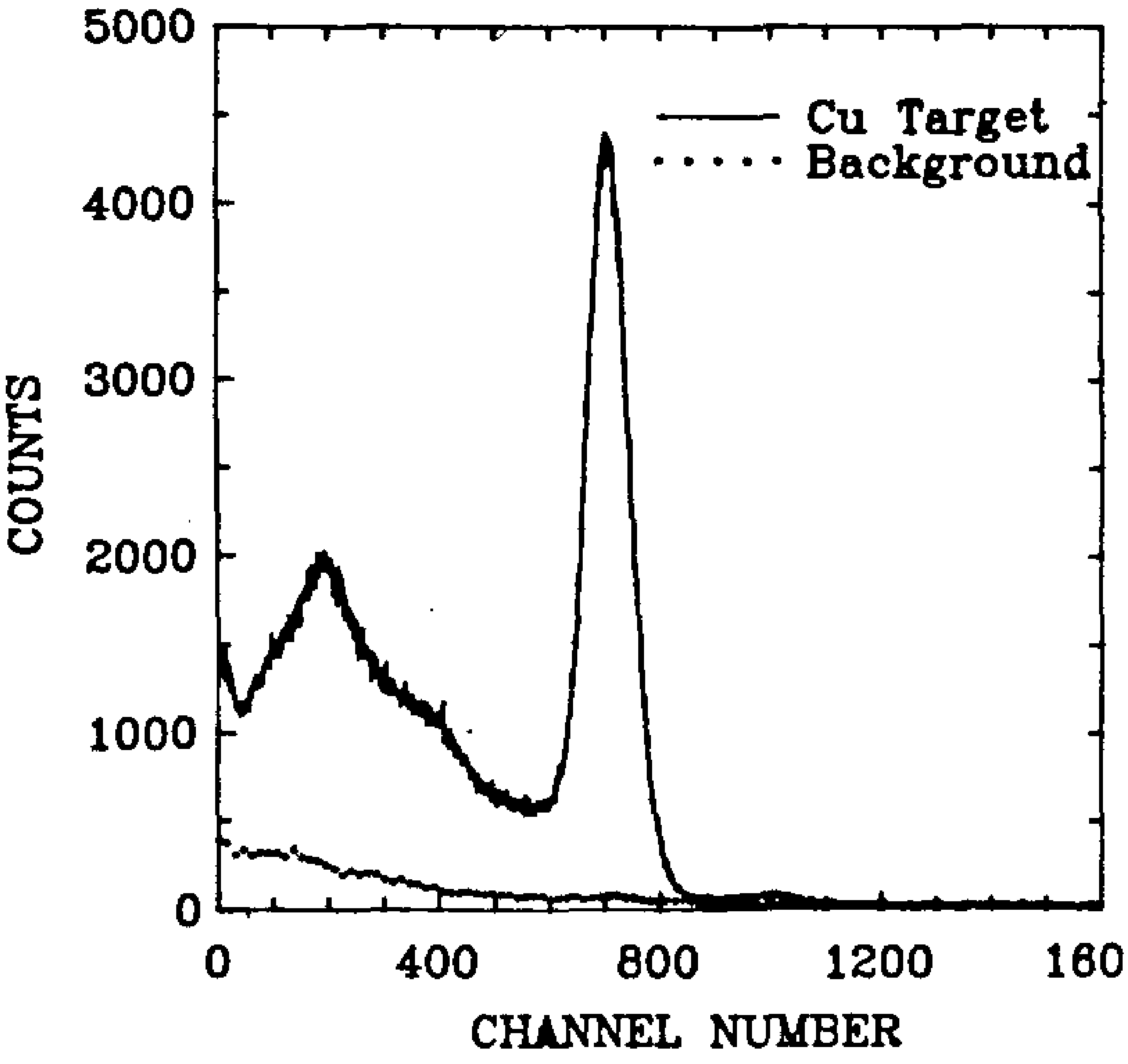

Figure 3. Gamma ray energy spectrum at the target obtained using $3'' \times 3''$ NaI detector, corresponding to beam transport activated (thick line) and switched off (dotted line). The prominent peak seen with the beam transport activated, corresponds to the photo peak of 511 keV annihilation gamma ray.

The number of slow positrons striking the target can be estimated by measuring the gated 511 keV gamma ray counts at the target using NaI detector and correcting for the solid angle and the detector efficiency. Based on this, we obtain about 3×10^4 slow $e^+ s^{-1}$ at the target. The moderator efficiency ε has been estimated from the slow positron flux by correcting for the transport losses. We obtain 2×10^{-5} for the moderation efficiency of the W(100) foil, which compares favourably with the earlier reported results[12,13]. Beam characteristics in terms of particle flux and beam size are quite satisfactory for carrying out regular experiments. Good reproducibility of the slow positron beam data on various targets has been obtained over long periods of time, with no adjustments to the settings of the beam transport system.

Experimental set up

Two types of experimental observables have been measured in the LEPB experiments (i) positronium fraction measurements via detection of three gamma annihilation events using a NaI detector and (ii) measurements of Doppler broadening of slow positron induced annihilation gamma ray energy using a high resolution intrinsic germanium detector, which are described below.

Positronium fraction measurements. Positronium (Ps) is a bound state of an electron and a positron, which can exist in two states[4], viz. *ortho*-positronium (O-Ps) which is a triplet state and a *para*-positronium which is a singlet state. It is well known that Ps formation is forbidden in bulk metals because of conduction electron screening of the two-particle bound state. In this context, the importance of solid surfaces became evident, with the first observation[14] of free Ps formation with high efficiency, when slow positrons impinged on solid targets in vacuum. In Ps fraction measurements, the number of implanted slow positrons diffusing back to the surface and getting converted into Ps at the surface/vacuum interface is measured. Ps formation and desorption at the sample surface critically depends on the surface conditions. Therefore, the Ps fraction measurements[14,15] are quite surface-sensitive. The $^3S_1$ (O-Ps) triplet state decays into three gammas with a continuous energy distribution from 0 to 511 keV. The three gamma energy spectrum has a characteristic broad maximum around 120 keV in the valley region to the left of the photo peak. This is in contrast to the two gamma annihilation mode resulting in the emission of discrete 511 keV gamma rays. In the Ps fraction measurements, the complete energy spectrum of gamma ray is measured using either a NaI detector or high resolution Ge detector. In our studies, we have used a 3″ × 3″ NaI detector for monitoring Ps fraction. The ratio of normalized area under the broad 120 keV peak and that of the 511 keV photo peak are used to deduce the Ps fraction[15], f, which is monitored as a function of incident positron beam energy.

Doppler broadening measurements. Slow positron beam spectroscopy, being a depth selective non-destructive technique, has at its heart the measurement[3] of Doppler broadened linewidth of the 511 keV annihilation line as a function of positron beam energy (E_p) usually in the range of a few eV to about 25 keV. In these measurements done with a high resolution intrinsic Ge detector, a lineshape parameter, viz. S-parameter is usually deduced as the fraction of the photo peak area lying in the central region of the Doppler broadening spectrum normalized to the total area of the photo peak. This S-parameter, which signifies the probability of annihilation events with valence electrons, is quite sensitive to the presence of atomic scale defects which trap positrons at a given depth. In the presence of positron trapping at defects, the Doppler broadening curve gets narrower, yielding a higher S-parameter. Thus, by analysing the variation of the S-parameter as a function of positron beam energy, the information pertaining to depth distribution of defects in the sample can be obtained. However, the deduced S-parameter is a linear combination of S_i values associated with various states, viz. surface, defected layers, bulk, etc., from which slow positrons can annihilate. Self-consistent modelling of the measured S vs E_p curve yields information on the depth distribution of defects in selected thin layers or interfaces, as the case may be.

Automation of slow positron data acquisition

The LEPB experiments, consist of measuring either Ps fraction or Doppler broadened lineshape at various beam energies starting from 200 eV to about 25 keV in small energy increments. Considering the attainable positron beam intensity at the sample, a typical counting time of about 1 h is required to record the gamma ray spectrum at a given beam energy. Thus, one needs to fix the beam energy and record the gamma ray spectrum for about 1 h and repeat this process for about 60 times to complete the total beam energy scan. Each experiment, therefore, extends over a period of 2 to 3 days. Hence, automation of the beam experiment will facilitate unattended data acquisition and smooth experimentation. The present LEPB is based on post-transport acceleration, wherein only the high voltage on the sample needs to be changed for varying the beam energy and no other beam transport parameter needs to be tuned. This elegant design feature enables the automation of data acquisition in beam experiments in a simple manner[16]. As shown in Figure 1, the setting of the high voltage on the sample and the acquisition of the data coming from the

Ge detector are being carried out by a PC using software program written in GWBASIC. The flow chart for the automation is given in Figure 4. Thus, the automation carries out the whole experimental scan, at the end of which a file is created consisting of S-parameter values for various positron beam energies. The performance of the automation system has been tested thoroughly and is being regularly used for carrying out beam experiments.

Experimental results

We present here some of the experimental results obtained in the initial phase, using the present LEPB facility. Surface sensitive positronium (Ps) fraction measurements have been made to study the effect of ad-atom overlayers and as well as the effect of near-surface defects in influencing the Ps formation on metallic surfaces. Apart from this, a bench-mark study of Doppler broadening measurements of defects at oxide–semiconductor interface, and a study of ion beam induced defect profiling in Si are presented to highlight the variety of problems that can be studied using LEPB.

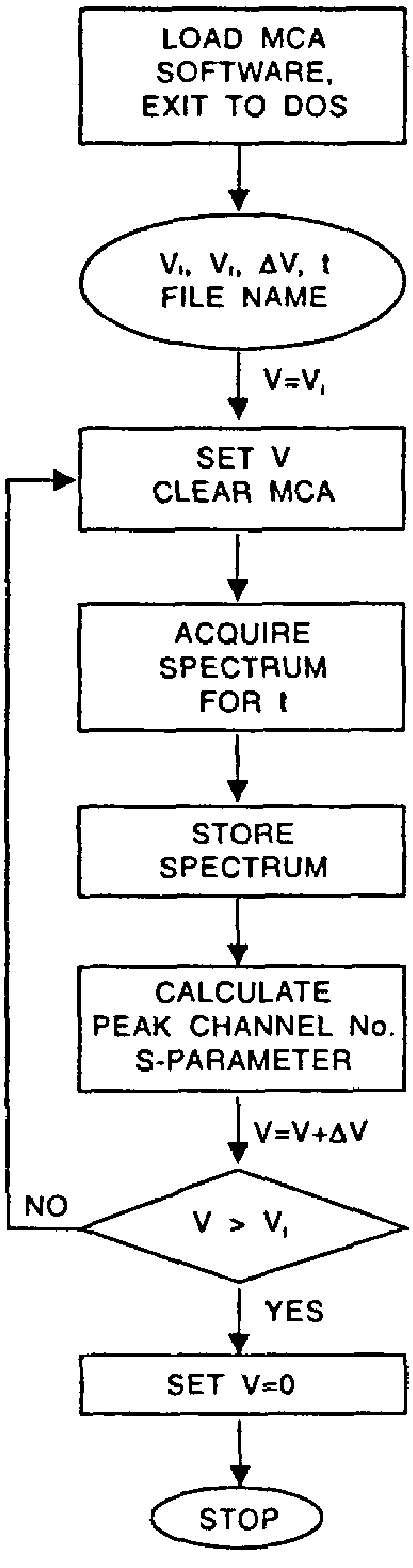

Figure 4. Flow chart of various steps being carried out in beam automation. V_i, V_f and ΔV are the initial, final and increment of high voltage applied to the sample, while t is the data acquisition time.

Positronium fraction studies at Cu surfaces

Measurements of Ps fraction (f) have been made on well-annealed Cu and oxygenated Cu surface using the experimental procedure discussed earlier. The results are shown in Figure 5, wherein f is plotted as a function of positron beam energy. As seen in Figure 5, in the case of well-annealed Cu, the value of f at the surface corresponding to low positron beam energy, is large. As the positron beam energy is increased, f decreases sharply and levels off. This observation indicates that Ps is formed with good efficiency at surface/vacuum interface. Once the positrons penetrate into deeper layers of the solid, the probability of back diffusion to the surface gets progressively decreased, thereby reducing the Ps fraction formed at the surface. A noticeable feature in Figure 5 is that the surface and bulk effects are clearly separable through Ps fraction measurements. As against annealed Cu, Cu surface covered with oxygen overlayers shows higher Ps fraction by nearly 15% for all incident positron energies (see Figure 5). This enhancement in Ps fraction may be explained as follows: At the surface, there are two competing options for positron to form a bound state, viz. positron bound to the potential well of the image forces just outside the

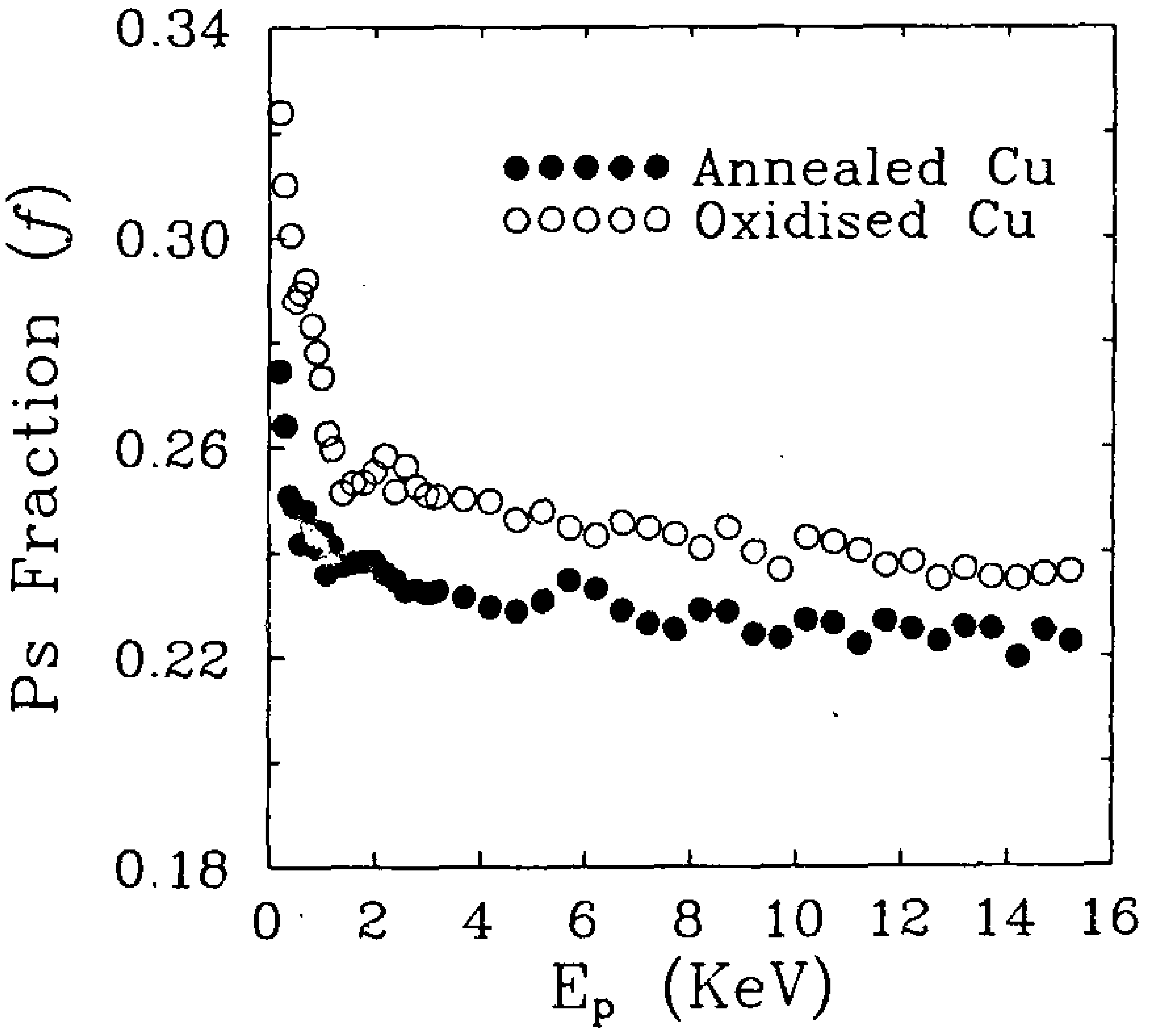

Figure 5. Positronium fraction, f, as a function of positron beam energy, E_p, for annealed and oxygenated Cu surfaces.

surface (positron surface state) and secondly, Ps formation at the surface. In the presence of oxygen adsorbed at the surface, the depth of the image correlation well becomes shallower, brought about by the screening electron density of oxygen atoms. Consequent reduction in positron binding to the surface state results in positron desorption even at room temperature. Positrons desorbed from the surface state are converted into Ps, as Ps formation is more energetically favoured. This explains the observed increase in Ps fraction for oxygenated Cu, as compared to oxygen free Cu. The present results in Figure 5 are in qualitative agreement with those reported earlier[17] on the effect of oxygen overlayers in Al single crystals. Apart from demonstrating the sensitivity for the presence of ad-atom overlayers, the present experiments show that using slow positron beams, one can monitor surface oxidation processes which are important in the study of semiconductor systems. The effect of near-surface defects on Ps formation in cold worked Cu has also been investigated[8]. Positron diffusion length L^+ has been extracted by analysing the experimental data using a simple diffusion model[8]. By providing yet another defect sensitive quantity in the form of L^+ , Ps fraction measurements extend the applicability of positrons for the study of defect-related phenomena in near-surface regions of materials.

Doppler broadening studies of SiO_2/Si interface

A study of SiO_2–Si interface[18] is of critical importance in the fabrication of semiconductor devices, particularly in the context of metal-oxide-semiconductor (MOS) technology. Considerable work is being carried out currently to study the purity, stability and defect properties of this interface. SiO_2–Si interface is ideally suited for characterization by slow positron beams, as shown by earlier works[19,20]. Using this as a bench-mark problem for our LEPB study, Doppler broadening measurements have been made on SiO_2–Si system as a function of positron beam energy and the results shown in Figure 6. Here, the SiO_2 layer of 110 nm thickness has been thermally grown on Si to produce the interface. The S-parameter values for the interfacial sample shown in Figure 6 has been normalized to that corresponding to a reference Si(100) sample. In the latter, where the native surface oxide layer has been removed by suitable etching, the measured S-parameter exhibits a constant behaviour for all incident positron beam energies. This constant value of the reference sample is taken as 1.0 in Figure 6. The salient features of the measurements on the SiO_2–Si system are as follows: (i) S-parameter is low at the surface. (ii) For low incident positron beam energies, S-parameter increases to a maximum. (iii) Upon further increase of the positron beam energy, S decreases to a minimum, exhibiting a dip at E_p of 3.5 keV. (iv) For higher positron implantation energy ($E_p > 3.5$ keV), S starts increasing and attains a saturation value, matching that corresponding to the bulk state of the reference Si sample.

The above observations in Figure 6 may be understood as follows. The low value of S-parameter corresponding to the surface of SiO_2–Si system arises because of the positron overlap with the oxygen core electron in the surface layer. After crossing the surface layer, positrons of low incident energies are stopped in the oxide layer. Since the positron diffusion length in oxide is small, most positrons annihilate in the oxide layer giving rise to an oxide signal in the form of a large S-parameter. For higher incident positron beam energies ($2.5 < E_p < 4$ keV), positrons reach the interface either through direct implantation or diffusion and get trapped at interfacial defects. These interfacial traps, having a characteristic local electron momentum distribution, gives rise to a distinct S-parameter corresponding to E_p of 3.5 keV. For large implantation energies ($E_p > 4$ keV), positrons are stopped at deeper layers beyond the interface and approach the bulk Si behaviour. Apart from demonstrating the slow positron sensitivity to different depth resolved signals in SiO_2–Si system, the present experiment offers scope for a detailed information on the nature, concentration and spatial distribution of defects at the interface through appropriate modelling of the experimental data.

Ion beam-induced defects in Si

A study of ion beam-induced defects in semiconductors

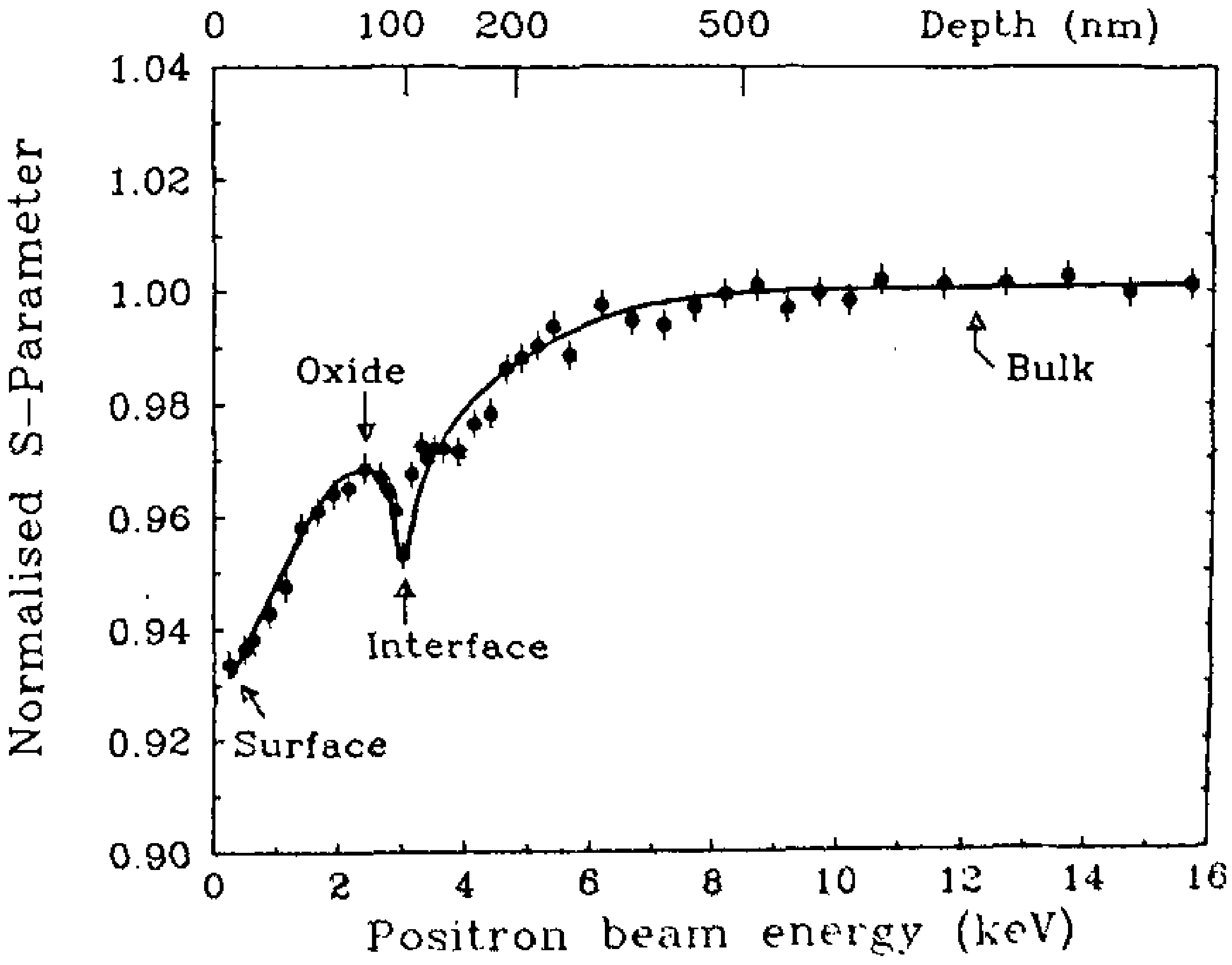

Figure 6. Normalized lineshape S-parameter plotted as a function of positron beam energy, E_p, for SiO_2–Si system. Positron beam energy converted into sample depth is indicated on top axis.

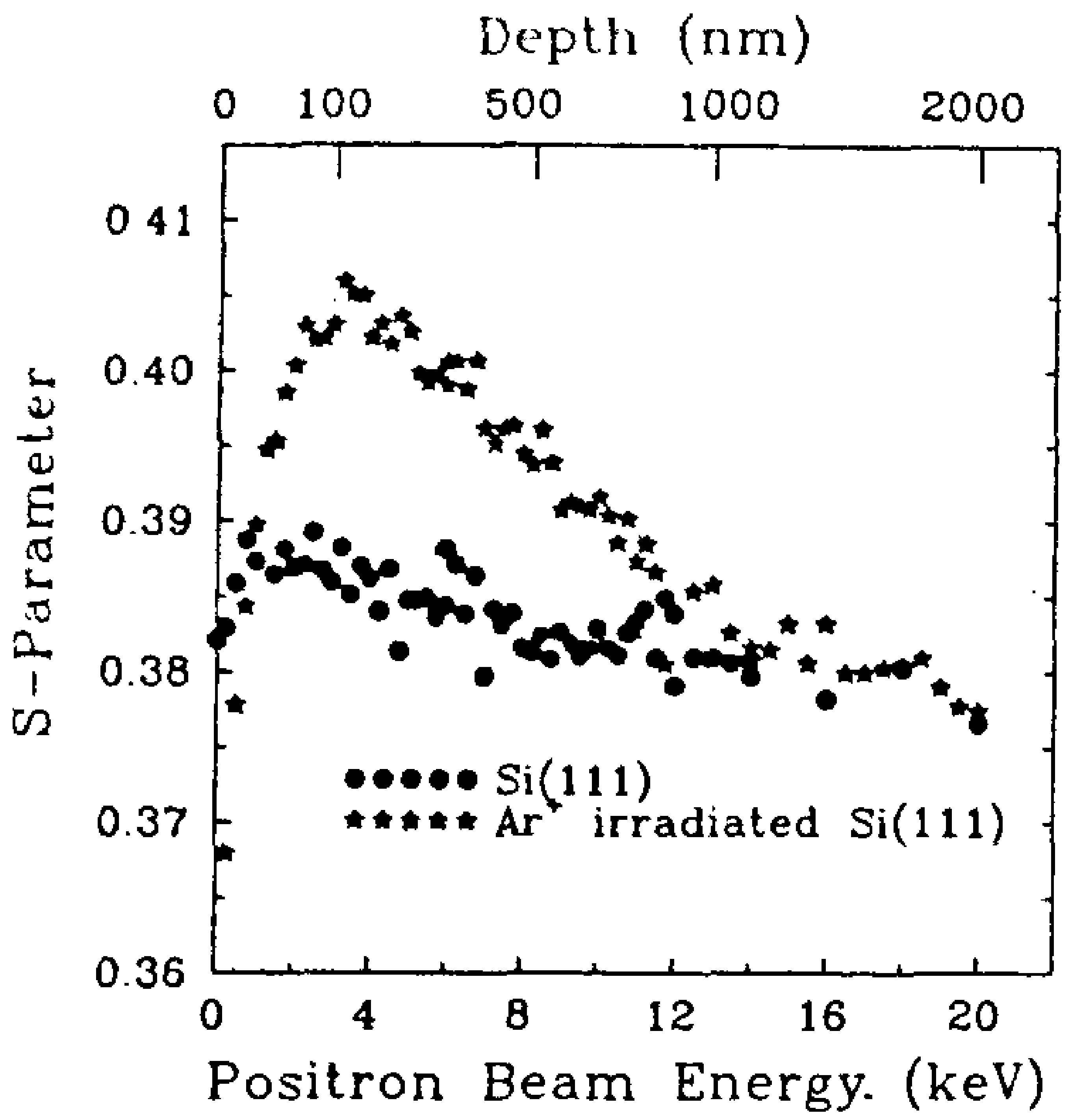

Figure 7. Lineshape *S*-parameter vs positron beam energy, E_p, for un-irradiated and 140 keV Ar irradiated Si(111) to a dose of 5×10^{16} cm^{-2}. Depth probed by the positron is indicated on top axis.

is of technological importance. With the advent of slow positron beams, a non-destructive study of depth profiling[21] of ion-induced defects in materials has become possible. We have studied[22] Ar ion-induced damage in Si(111) using our LEPB. Samples of 250 μm thick Si(111) have been irradiated with 140 keV Ar ions to a range of doses starting from 5×10^{14} to 5×10^{16} ions cm^{-2} at room temperature using a 150 kV ion implantor. Calculations using the TRIM code[23] indicate the average range of Ar ions to be around 140 nm, while the accompanying lattice damage has an asymmetric distribution with a maximum around 90 nm. Doppler broadening measurements have been carried out on these samples as a function of positron beam energy and the results are shown in Figure 7. The sample depth corresponding to the respective positron beam energy is indicated on top axis. The un-irradiated Si sample has low *S*-parameter at the surface and it increases slightly with depth before levelling off in the deeper layers. The variation of *S*-parameter for Si irradiated with 5×10^{16} Ar cm^2 is also shown in Figure 7. As compared to the un-irradiated case, the irradiated sample shows a large increase in *S*-parameter around E_p of 3.5 keV which corresponds to a depth of maximum defect concentration induced by ion irradiation. Beyond E_p of 3.5 keV, the *S*-parameter gradually decreases and attains un-irradiated values at E_p of 12 keV. Thus, the present LEPB experiments indicate that 140 keV Ar ions create a lattice damage in Si which starts from the surface, peaks around 100 nm and spreads up to a depth of 1000 nm. Having established slow positron sensitivity to the presence of non-uniform defect distribution in the sample induced by Ar ion irradiation, experiments are in progress to create and study amorphous zones in selective depth intervals in Si with increasing Ar ion dose.

Summary and conclusions

Monoenergetic positron beams of tunable low energy have emerged as a viable defect spectroscopic tool for our understanding of the characteristics of thin-layered structures, interfaces and multi-layers, because of their non-destructive nature and depth-resolved defect sensitivity. The salient design features of the positron beam facility at our laboratory are its UHV compatibility, compactness, electrostatic beam extraction, magnetic transport and post-transport acceleration to the desired energy. Successful functioning of various in-house designed and installed subsystems has led to the smooth commissioning and satisfactory performance of the integrated system as a research grade facility. Experimental results in terms of slow positron studies on Cu surfaces, semiconductor interfaces and ion beam-induced defect profiling in semiconductors have been presented. These show the capability of the technique for a detailed characterization of many modern thin film materials, which are of technological importance. Lastly, the development and operation of the present LEPB facility opens up the possibility for future developments of brightness enhanced microbeams towards realizing low energy positron diffraction[24] (LEPD), positron-induced Auger electron spectroscopy[25] (PAES) and positron reemission microscope (PRM)[26], which have potential applications in the area of surface research.

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1. Brandt, W. and Dupasquier, A. (eds), *Positron Solid State Physics*, North Holland, Amsterdam, 1983.
2. Viswanathan, B. and Sundar, C. S. (eds), *Positron Annihilation Studies in Materials Science*, Meshap Science, 1996; See *Metals, Materials and Processes*, vol. 8, no. 1.
3. Schultz, P. J. and Lynn, K. G., *Rev. Mod. Phys.*, 1988, **60**, 701–779.
4. Mills Jr., A. P., in ref. 1, pp. 432–509.
5. Viswanathan, B. and Amarendra, G., in *Positron Annihilation and Compton Scattering* (eds Sharma, B. K., Jain, P. C. and Singru, R. M.), Omega Scientific Publishers, New Delhi, 1990, p. 29–43.
6. Canter, K. F. and Mills Jr., A. P.; *Can. J. Phys.*, 1982, **60**, 551–557.
7. Amarendra, G., Viswanathan, B., Venugopal Rao, G., Thomas Kutty, K. V., Purniah, B. and Gopinathan, K. P., *Slow Positron Beam Techniques for Solids and Surfaces* (eds Ottewitte, O. and Weiss, A. H.), AIP Conf. Proc., 1994, **303**, 452–461.
8. Amarendra, G., Venugopal Rao, G. and Viswanathan, B., *Indian J. Pure Appl. Phys.*, 1996, **34**, 718–726.
9. Amarendra, G. and Viswanathan, B., in ref. 7, p. 441–451.
10. Canter, K. F., Lippel, P. H., and Nguyen, D. T., *Positron Studies of Solids, Surfaces and Atoms* (eds Mills Jr., A. P., Crane, W. S., and Canter, K. F.), World Scientific, Singapore, 1986, pp. 207–220.
11. Schödlbauer, D., Sperr, P., Kögel, G. and Triftshäuser, W., *Nucl. Instrum. Meth. Phys. Res.*, 1988, **B34**, 258–268.
12. Amarendra, G., Canter, K. F., and Schoepf, D. C., *J. Appl. Phys.*, 1996, **80**, 4660–4664.
13. Willutzki, P., Stormer, J., Britton, D. T., Kögel, G., Sperr, P., Steindl, R., and Triftshäuser, W., in ref. 7, pp. 542–549.

14. Canter, K. F., Mills Jr., A. P. and Berko, S., *Phys. Rev. Lett.*, 1974, **33**, 7–10.
15. Mills Jr., A. P., *Phys. Rev. Lett.*, 1978, **41**, 1828–1831.
16. Parimala, J., Purniah, B., Venugopal Rao, G., Amarendra, G. and Viswanathan, B., *J. Instrum. Soc. India*, 1996, **26**, 104–109.
17. Lynn, K. G., *Phys. Rev. Lett.*, 1980, **44**, 1330–1333.
18. Balk, P. (ed.), *The Si–SiO_2 System*, Materials Science Monographs, Elsevier Science Publishers, Amsterdam, 1988, vol. 32.
19. Bent Nielsen, Lynn, K. G., Yen-C Chen and Welch, D. O., *Appl. Phys. Lett.*, 1987, **51**, 1022–1023.
20. Asoka-Kumar, P., Lynn, K. G., and Welch, D. O., *J. Appl. Phys.*, 1994, **76**, 4935–4982.
21. Triftshäuser, W. and Kögel, G., *Phys. Rev. Lett.*, 1982, **48**, 1741–1744.
22. Venugopal Rao, G., Amarendra, G., Nair, K. G. M. and Viswanathan, B., *Solid State Physics (India)*, 1996, **C39**, 150.
23. Ziegler, J. F., Biersack, J. P. and Littmark, U., *The Stopping and Range of Ions in Solids*, Pergamon, New York, 1985, vol. I.
24. Chen, X. M., Canter, K. F., Duke, C. B., Paton, A., Lessor, D. L. and Ford, W. K., *Phys. Rev.*, 1993, **B48**, 2400–2411.
25. Weiss, A., in *Surface Imaging and Visualization* (ed. Hubbard, A. T.), CRC Press, NY, 1995, pp. 617–633.
26. Canter, K. F., Amarendra, G., Vasumathi, D., Wesley, S. A., Xie, R., Mills Jr., A. P., Sabatini, R. L. and Zhu, Y., *Appl. Surf. Sci.*, 1995, **85**, 339–344.

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MEETINGS/SYMPOSIA/SEMINARS

XII Carbohydrate Conference

Date: 20–21 November 1997
Place: Lucknow

Topics include: Carbohydrates in chemical transformations; Plants and microbial polysaccharides: isolation, characterization, structure elucidation and utilization; Unusual sugars of biological importance; Industrial polysaccharides: Production and utilization; Complex carbohydrates; Transition metal saccharides chemistry and biochemistry.

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National Conference on Impact of Biotechnology and Modern Horticulture on Rural Development

Date: 20–22 November 1997
Place: Calcutta

The Conference will provide a common platform for the scientists, agro and biotechnologists, government and corporate sector people and NGOs of our country to meet and exchange their ideas and knowledge on varied aspects of interdisciplinary areas of biotechnology and agro-horticulture for environment-friendly sustainable rural development in India.

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International Workshop on 'Application of Remote Sensing and GIS for Sustainable Development' and a National Symposium on 'Remote Sensing for Natural Resources with Special Emphasis on Infrastructure Development'

Date: 24–25 and 26–28 November 1997
Place: Hyderabad, India

The advantages of using high resolution IRS-1C data for various applications, particularly the infrastructure development, will be one of the highlights.

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