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A Real-Time *S*-Parameter Imaging System

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Obtaining a lateral S-parameter image scan from positrons implanted into semiconductor devices can be a helpful research tool both for localizing device structures and in diagnozing defect patterns that could help interpret function. S-parameter images can be obtained by electromagnetically rastering a variable energy positron beam of small spot size across the sample. Here we describe a general hardware and software architecture of relatively low cost that has recently been developed in our laboratory which allows the whole sub-surface S-parameter image of a sample or device to be obtained in real time. This system has the advantage over more conventional sequential scanning techniques of allowing the operator to terminate data collection once the quality of the image is deemed sufficient. As an example of the usefulness of this type of imaging architecture, S-parameter images of a representative sample are presented at two different positron implantation energies.

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1. Introduction

It is quite common to encounter small device structures of millimeter or sub-millimeter dimension that need their sub-surface structures to be studied with a positron beam. Typical examples of such devices are photodiodes, light emitting diodes and MOS structures that have diameters typically in the $100-500$ μm range. Functional or defect studies of such structures would require a positron beam of equal or smaller diameter. There is also a class of positron experiments in which the energy levels of vacancy defects are populated with electrons either by electrical pulsing or through laser excitation and then allowed to thermally ionize with time [1]. This category of experiment is also best carried out with either

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Schottky contacts or laser sources of sub-millimeter dimension using a positron beam of similar dimension.

Positron beam studies on small dimension samples can present practical problems in localizing the device structure in question. In principle localization can be achieved using a channel electron multiplier array (CEMA) equipped with a phosphor screen to locate the beam and after having located it to then move the device structure down into the exact location [2]. This in practice, however, is quite difficult requiring very accurate measurement of the device position and the assumption that after having retracted the multichannel plate (MCP) and after having lowered the sample into position that the positron beam itself has not moved. Clearly there is an advantage in circumventing this procedure by using the positron beam itself to locate the device structure in question. Here, prior to the specified experiment, a lateral 2D image is formed based on the 511 keV annihilation line "shape" parameter "S" [3] as sampled across the surface (or sub-surface) of a particular device structure. Once the device structure in question is located by way of this 2D S-parameter image the positron beam can be controlled to remain at the referenced location at all beam energies. Such a procedure greatly enhances the ability to carry out functional or defect structural positron annihilation studies on a device. This practical advantage is one of the main reasons for developing the real-time S-parameter imaging system developed in this work.

Apart from the practical ability of being able to simply locate a target structure, S-parameter image formation has other advantages. A good quality S-parameter image would require data accumulation times ranging from a few hours to several days (depending on the beam intensity). Such images, once formed, could provide useful information. For example one might be scanning a device or semiconductor material to check on the uniformity of the defects present in the material [4]. The fact that the positron beam is energy tunable would mean that such 2D images could be formed at a variety of depths allowing some form of 3D defect map to be produced. Alternatively device function could be investigated by electrically pulsing a gate or metallization and seeing how the image changed after certain elapsed times. Such studies could allow the user to perform functional studies of a device by following the charge state of deep-level defects in a device.

This paper is organized as follows. In the next section of this paper we describe the sub-millimeter focusing action of the University of Hong Kong positron beam system and how the beam spot is electromagnetically rastered across the sample/device surface. Then we give details of the hardware and software processing that allows us to form a S-parameter image in real time. In Sect. 3 we show some examples of S-parameter images taken with the system and finally in Sect. 4 we conclude with some ideas on future developments.

2. The S-parameter imaging system

2.1. Beam focusing

The University of Hong Kong electromagnetically scanning positron system comprises a novel hybrid optics that allows for both efficient collection of moderated positrons and millimeter focusing at the target [5]. The primary positron gun is shown schematically in Fig. 1. Positrons from a 20 mCi, Ti encapsulated ^{22}Na source "S" are moderated by a 1600°C *ex situ* annealed 12 layer mesh tungsten moderator "M" [6] and work-function ejected positrons are collected using the standard electrostatic Soa geometry [7]. Here it should be noted that the oil cooled solenoid that surrounds this primary optics is fed with a current of ≈ 20 A such that the 100 Gs magnetic field generated from the main external field coils (not shown) is completely neutralized. That is the Soa extraction lens operates in a magnetic field free region. After extraction the positrons pass through a focusing Einzel lens system that both focuses and accelerates them to an energy of 7.5 keV into the "magnetic funnel" and the main transporting magnetic field. The positrons come to a focus just inside this lens (focus "f_1") and then after acceleration (focus "f_2"). The positrons are then transported a distance of ≈ 2 m under cyclotron motion [as shown in the inset to Fig. 1] to the target through a series of repetitive nodes (foci) and antinodes. The magnetic field is adjusted

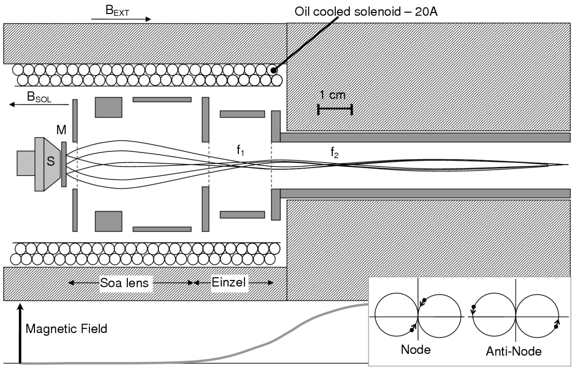

Fig. 1. Beam focusing. The hybrid lens system of The University of Hong Kong positron beam: $M = 12$ layer tungsten mesh moderator, f_1 and f_2 = primary and secondary foci. Shown is the oil cooled solenoid, which is internal to the vacuum and which produces back magnetic field B_{SOL} to exactly neutralize the external magnetic field B_{EXT} of 100 Gs that is produced from coils outside the vacuum. The shaded areas are all lead radiation shielding (4% Sb). Inset shows the cyclotron motion trajectory structure as seen from an end-on view. The beam passes from "node" (foci) to "anti--node" along the beam with the magnetic field tapered so as to bring a "node" onto the target.

around the target so as to bring the last node to focus on the target. Just after the primary 7.5 keV gun described, the beam is filtered (between the 3rd and 5th foci) with an ExB velocity filter so as to remove gamma radiation and non-moderated positrons. After the velocity filter the beam traverses a 1 meter flight path where it is subject to the electromagnetic deflection supplied by two deflection saddle coils [8, 9]. These are used to bring about the x and y deflections of the beam required for the rastering action (see next section). The quality of the target beam spot was checked with using the CEMA-phosphor detector. It was found that the beam had a spot size of 1 mm in the range of energies from 5–20 keV.

2.2. Beam rastering

The rastering of the positron beam across the target sample was realized by driving currents through the x and y saddle coils (see Fig. 2) [8–10]. These saddle coils are located before the linear accelerator and target, so that the deflection is not affected by the final beam energy. Since the coils were relatively long compared to the pitch length of the cyclotron motion the deflection was adiabatic. As shown in Fig. 2 the x and y coils were driven with a saw-tooth wave provided by current amplifiers and function generators. The frequency on the x and y drives were 10 and 0.1 Hz respectively. The integrity of the rastering was checked by observing the image on the CEMA-phosphor detector.

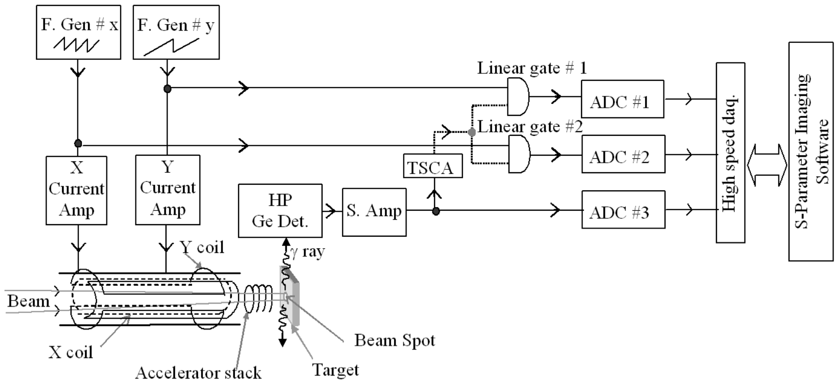

Fig. 2. General architecture of the S-parameter imaging system (see text for details).

2.3. Formation of the S-parameter matrix

Figure 3 shows schematically the positron probe rastering across a sample surface. It is noted that each annihilation event can be classified by a measurement "triplet" (x, y, E_γ) where x, y are the measurements of the x and y positions of the beam at the time of the event and E_γ is the energy of the annihilation photon. As seen from Fig. 2 the measurements of x and y are obtained from the function

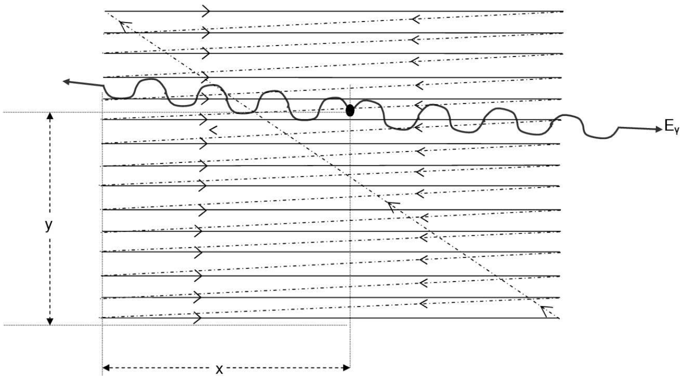

Fig. 3. The scheme of beam rastering showing the measurement triplet (x, y, E_γ) for each annihilation event.

generators using a 14 bit nuclear ADC. The value of E_γ is also similarly obtained using a 14 bit ADC. The "triplet" events are, after digitization, fed into a high speed data acquisition card [9].

The triplet events are software processed as shown in Fig. 4. First the x and y data are binned within the integer range (0, n) where n can be set at either 16, 32, 64, or 128. The resulting integers "i" and "j" that result are used to index two matrix arrays $\boldsymbol{C}$ and $\boldsymbol{T}$. With regard processing E_γ all events falling within the 511 keV peak are considered as "T" (= total peak) events. In practice if the event is within ±4 keV of the 511 keV line it is considered as a "T" event. If a "T" event is registered then the software augments by one the content of the (i, j) matrix element in the $\boldsymbol{T}$ matrix. The software then proceeds to check if the "T" event is also a "C" (= central region) event or not. An event is classified as a "C" event if its E_γ lies within a narrow region set symmetrically about the 511 keV peak. The width of this region is determined by trial and error at the beginning of the experiment to obtain an S-parameter ($= C/T$) as averaged over

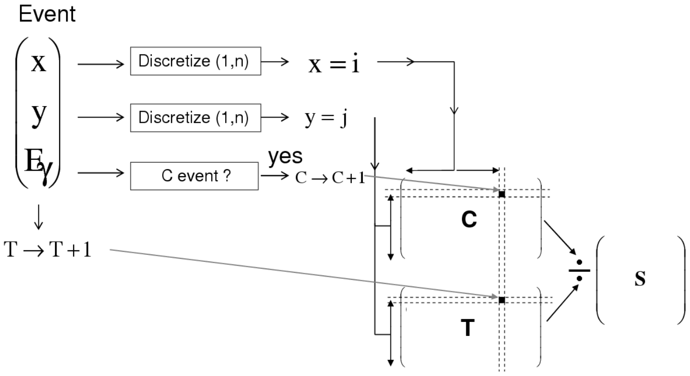

Fig. 4. Schematic diagram showing the construction of the $\boldsymbol{S}$ matrix.

the whole sample of approximately 0.5. If an event is classified as a "C" event the software augments the $\boldsymbol{C}$ matrix at the element indexed by (i, j). After a given time the elements at each (i, j) coordinate in the $\boldsymbol{C}$ and $\boldsymbol{T}$ matrices can be divided to give what is the "S"-parameter value corresponding to annihilation photons that were emitted from that corresponding (x, y) position. That is one obtains $\boldsymbol{S}$, the S-parameter "image" matrix as

$$\boldsymbol{S} = \begin{pmatrix} \frac{C_{11}}{T_{11}} & \frac{C_{12}}{T_{12}} & \frac{C_{13}}{T_{13}} & \cdots & \frac{C_{1n}}{T_{1n}} \\ \frac{C_{21}}{T_{21}} & \frac{C_{22}}{T_{22}} & \frac{C_{23}}{T_{23}} & \cdots & \frac{C_{2n}}{T_{2n}} \\ \frac{C_{31}}{T_{31}} & \frac{C_{32}}{T_{32}} & \frac{C_{33}}{T_{33}} & \cdots & \frac{C_{3n}}{T_{3n}} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \frac{C_{n1}}{T_{n1}} & \frac{C_{n2}}{T_{n2}} & \frac{C_{n3}}{T_{n3}} & \cdots & \frac{C_{nn}}{T_{nn}} \end{pmatrix}. \quad (1)$$

The software makes no attempt to compensate for the background counts in the annihilation line because these only give minor changes in the absolute value of the S-parameter. Moreover, the peak position is checked in a certain time interval (1–10 minutes) to monitor the electronic drift and an automatic feedback loop ensures that the central region is kept locked on the peak center.

The supporting software of the imaging system is efficient for real-time data acquisition and image processing. In the system, the processing time and use of system resources are constantly monitored and optimized for producing a high resolution S-parameter image of the sample in real time. The standalone imaging software, which runs on a general purpose personal computer, possesses special features with its embedded specialized algorithms and techniques that provide the user with adequate freedom for analyzing various aspects of the image in order to obtain a clear inference of the defect profile while at the same time keeping automatic track on the instrumentation and hardware settings. The image resolution (number of pixels) can be user optimized according to the total number of annihilation events.

3. Results

The first phase of constructing the real-time S-parameter imaging system was completed in January 2004 and the first set of results were reported at the IS&T/SPIE 16th Annual Symposium on Electronic Imaging Science [8]. At this phase however, the improved hybrid lens focusing design of the HKU beam [5] running without an operative ExB filter for removing fast positrons and without variable energy capability. The beam quality was thus limited with some contamination from fast positrons and the beam energy was fixed at 7.5 keV. Moreover the beam spot size at the target was of $\approx$ 1.5 mm diameter. Even with these limitations, however, a reasonable image could be obtained for a test sample.

By August 2004 improvements to the positron beam included a working ExB filter and variable acceleration stage allowing a more complete study to be per-

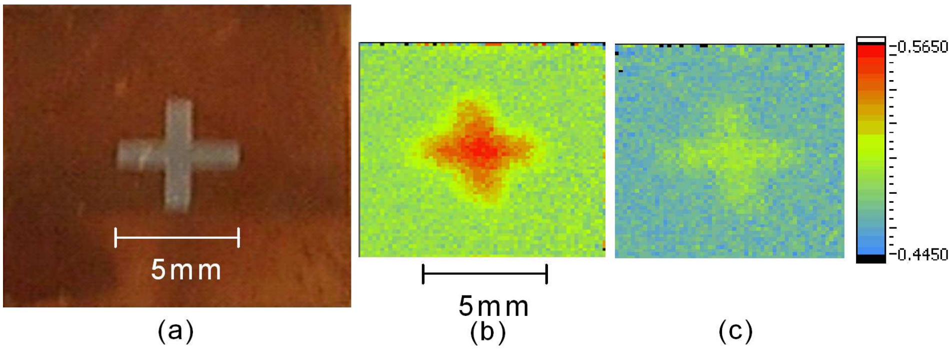

Fig. 5. S-parameter images taken with the variable energy beam (spot diameter $\approx$ 1 mm) for a 1 μm thick Al "cross" on Cu substrate: (a) photograph, (b) image taken at 7.5 keV beam energy, (c) image taken at 20 keV beam energy.

formed. Moreover, the beam spot size at the target had been reduced to 1 mm diameter. The improved beam in conjunction with the S-parameter imaging system was tested by imaging at different energies a sample consisting of a cross shape of Al evaporated onto a copper substrate. The results for beam energies of 7.5 keV and 20 keV are shown in Fig. 5. At 7.5 keV beam energy the mean implantation depth for positrons is 0.36 μm which using the implantation profile of Vehanen et al. [11] gives some 99.96% of positrons stopping in and annihilating from the Al. However, by the same calculation at 20 keV the mean implantation depth is 1.79 μm and only 27% of the positrons are stopping in the Al. While an S-parameter image is seen at both energies, the difference in contrast is obvious. The cross structure is less clearly seen in the 20 keV image as a result of the smaller fraction of positrons stopping in the aluminum.

4. Conclusions and future prospects

A real-time S-parameter imaging system has been constructed. It has been found that with this system working at a rate of 500 cps into the annihilation line a strong feature (i.e. one with a large difference in S-parameter values across its surface) can be localized within an hour of data accumulation. This demonstrates that the imaging system can be potentially useful in localizing surface device structures. It is also planned to use the system for lateral imaging of material defects. Moreover, it is hoped to extend the imaging system's capabilities for lateral defect mapping by extending it to provide additional W and R parameters images [12]. Such images would help to distinguish between changes in S-parameter value resulting from variations in defect type rather than concentration. It might be hoped that these advanced imaging systems will achieve wider application in the positron research community and as such provide an easy and confirmative visual approach towards defect profiling. The use of defect profiling in electronic devices of micron and sub-micron scale is likely to be important in the future especially as more positron beams are manufactured with micron spot size.

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References

[1] C.D. Beling, S. Fung, *Mater. Sci. Forum* **363-365**, 25 (2001).

[2] P.G. Coleman, in: *Positron Beams and Their Applications*, Ed. P.G. Coleman, World Scientific, Singapore 2000, p. 33.

[3] I.K. MacKenzie, J.A. Eady, R.R. Gingerich, *Phys. Lett. A* **33**, 279 (1970).

[4] T.E.M. Staab, C. Zamponi, M. Haaks, I. Müller, S. Eichler, K. Maier, *Mater. Sci. Forum* **445-446**, 510 (2004).

[5] C.K. Ceung, P.Y. Kwan, Y.Y. Shan, P.S. Naik, H.M. Weng, C.D. Beling, S. Fung, *Mater. Sci. Forum* **445-446**, 465 (2004).

[6] F. Saito, Y. Nagashima, L. Wei, Y. Itoh, A. Goto, T. Hyodo, *Appl. Surf. Sci.* **194**, 13 (2002).

[7] K.F. Canter, P.H. Lippel, W.S. Crane, A.P. Mills, Jr., in: *Positron Studies of Solids, Surfaces and Atoms*, Eds. A.P. Mills, Jr., W.S. Crane, K.F. Canter, World Scientific, Singapore 1986, p. 199.

[8] P.S. Naik, C.D. Beling, S. Fung, in: *Real-Time Imaging VIII*, Eds. N. Kehtarnavaz, P.A. Laplante, *Proc. of SPIE-IS&T Electronic Imaging*, SPIE Vol. 5297, 2004, p. 294.

[9] Patent specification, *Real-Time S-parameter Imager*, P.S. Naik, C.D. Beling, S. Fung, USA patent application number 10/890,723, filed on 14th August 2004.

[10] P.S. Naik, C.D. Beling, S. Fung, *Mater. Sci. Forum* **445-446**, 501 (2004).

[11] A. Vehanen, K. Saarinen, P. Hautojärvi, H. Huomo, *Phys. Rev. B* **35**, 4606 (1987).

[12] S. Mantl, W. Triftshäuser, *Phys. Rev. B* **17**, 1645 (1978).