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A novel sensor for ion electron emission microscopy

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Abstract

An ion electron emission microscope (IEEM) to be installed at the SIRAD heavy ion irradiation facility at the 15 MV tandem accelerator of the INFN Legnaro laboratory (Italy) will be used to characterize the sensitivity of electronic devices to single event effects (SEE) to ion impacts with micrometric lateral resolutions. The secondary electrons emitted by ion impacts from the target surface are transported and focused by an electron microscope onto a micro-channel plate (MCP) detector coupled to a fast phosphor. The luminous signal is then detected by a position sensitive photon detector located outside the vacuum chamber. The high repetition rates and high spatial resolution, required to temporally distinguish ion impacts for SEE studies and avoid degrading of the initial resolution of the IEEM and MCP are met by the system, presented here for the first time, based on two orthogonal linear CCDs.

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1. Introduction: SIRAD and IEEM applications

The SIRAD irradiation facility located at the 15 MV tandem accelerator of the INFN Legnaro laboratory, Padova (Italy), is dedicated to the radiation damage studies in silicon detectors, semiconductor microelectronic devices and systems for high energy physics and space applications [1]. Device characterizations such as SEE cross-section measurements are routinely performed using a wide selection of ion species, from Li up to Au, to cover a broad interval of linear energy transfer (0.35–80 MeV $\mathrm{cm}^2\,\mathrm{mg}^{-1}$) with energies and ranges suitable to test most modern technology devices. A very important part of the research and validation program at SIRAD is the study of SEE in various application specific integrated circuits (ASIC) and, more generally, state-of-the-art commercial devices such as SDRAM, FPGA, FLASH, and power devices.

To extend this successful program to include micrometric characterizations of the device under test (DUT), the SIRAD group is developing ion electron emission microscopy (IEEM) capabilities. In the IEEM technique the ion beam is not

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micro-focused on the DUT and the position of each single ion impact is reconstructed with micrometric resolution by collecting secondary electrons emitted from the target surface and transferring them, by means of an electron emission microscope, onto a fast two-dimensional electron detector [2–4]. For SEE or ion beam induced charge collection (IBICC) studies the *X*, *Y* transverse coordinates and the time *T* of the random ion impacts are then correlated with events induced in the DUT to establish a sensitivity map [5]. This novel IEEM technique is somewhat complementary to the consolidated nuclear microprobe technique that builds up sensitivity maps with lateral resolutions of the order of 0.5–1.0 μm by moving a micro-focused beam spot systematically across the DUT with micrometric precision.

2. The SIRAD IEEM

The SIRAD IEEM system is based on a commercial photon electron emission microscope (PEEM): secondary electrons emitted by the ion impact from the portion of a DUT in the field of view are transferred and focused with a magnification factor of ∼160 onto a 40 mm diameter two-stack MCP detector. The latter is directly coupled to a thin phosphor screen (P47) to generate a luminous signal with a resolution of 16 line-pairs/mm, corresponding to a nominal lateral resolution of 0.4 μm on the DUT. The nominal resolution may be improved by a factor 2 by using a higher resolution MCP and is ultimately limited by the channel structure of the MCP. Indeed phosphor screens have a micro-crystal structure and give resolutions better than 100 lp/mm. Nevertheless, the microscope suffers from aberrations that are limited by means of a contrast diaphragm: our standard maximum aperture of 300 μm ensures an intrinsic resolution of 0.6 μm over a field of view of 250 μm; using a 200 μm diaphragm, the resolution improves to 0.4 μm. However with a 300 μm diaphragm aperture the secondary electron transmission from the DUT surface through the IEEM and onto the focal plane is 10%, a factor two larger than what an aperture of 200 μm would ensure. In addition to this the MCP itself is 55% efficient. By depositing a thin gold layer (20–40 nm) on the DUT surface, to ensure good secondary electron emission, it is expected that the IEEM will have, at the level of the phosphor screen of the MCP, an ion impact detection efficiency of 45% for 100 MeV C ions, reaching full efficiency for ions with $Z > 25$ [6].

The SIRAD IEEM will be mounted axially on the beam line with an annular MCP-phosphor stack to allow for ion impacts normal to the DUT. The luminous signal, transported off-axis out through a view port over a distance of 25 cm by means of a mirror and a system of lenses onto a two-dimensional photon detector placed outside the irradiation chamber (Fig. 1), must be detected precisely and without dead times. Since this scheme suffers from a 1% photon collection efficiency the production of a large number of photons per ion impact is required to guarantee a high spatial resolution of the detection system. Gains up to 10^7 are easily achievable using two-stack MCPs and for each electron exiting the MCP about 40–80 photons with mean wavelength of 400 nm are created by the P47 phosphor. The choice of P47 also satisfies the requirement that the opto-electronic IEEM have a high repetition rate: the characteristic time is less than 100 ns. This said, we want to stress the combined request that the effective lateral resolution of the IEEM be degraded as little as possible while achieving high repetition rates is the real challenge.

Commercial two-dimensional CCD arrays are the standard detectors used for the PEEM surface analysis technique. They are sensitive to low intensity luminous signals, but have long readout times that limit the useful ion fluxes in SEE applications. Considering a typical bi-dimensional CCD sufficient to match the resolution of the IEEM, for one-output 1024×1024 array the frame rate is 30 fps (total data rate 40 MHz). To avoid too many frames with multiple hits the ion flux in the field of view of the IEEM must be of the order of 10 ion impacts/s. This limits the use of CCD arrays in SEE studies to devices that presents a large total cross-section in the field of view. Rates of thousands of ions per second in the IEEM field of view are in fact needed to perform most SEE

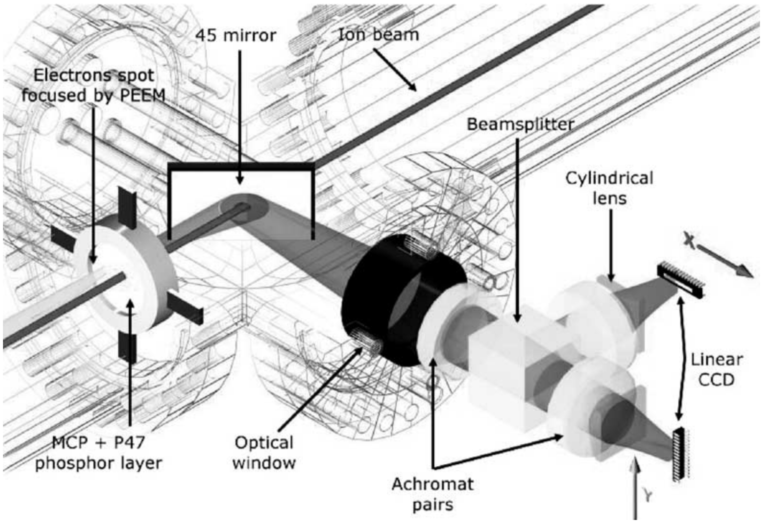

Fig. 1. Schematic representation of the SIRAD opto-electronic solution with the newly developed sensing system for fast IEEM applications.

cross-section measurements in a reasonable amount of time.

3. SIRAD opto-electronic solutions

We have developed two solutions that ensure optimal flexibility for SEE studies, keeping high spatial resolution and repetition rates three orders of magnitude greater than those of CCD arrays.

The first solution, based on a commercial 2×2 cm^2 square UV-enhanced high linearity position sensitive device (PSD) that works on the lateral-effect photodiode principle, was presented in detail at the ICNMTA 2002 conference [4].

The PSD system is fast (40 kHz) but suffers from two drawbacks. First the lateral resolution depends on the intensity of the luminous spot: to measure the position of the luminous spot with a lateral resolution of 1/500th of the PSD size requires at least 9×10^8 photons and consequently a large MCP gain (few 10^8). Rather than to degrade immediately the IEEM resolution by substituting the two-stack MCP detector with a high gain multi-stack MCP we chose to use a high resolution image intensifier (27 lp/mm) placed outside the irradiation chamber in front of the PSD. The second drawback is due to multiple signals, multiple ion impacts or hot spots (because of non-uniform electron emission or hot MCP channels). Given the ion rates employed for SEE studies, multiple ion hits will not pose a real problem for these fast detector systems. On the contrary hot MCP channels may be present. Non-uniformities in electron activity pose very severe problems for the PSD system as the position coordinates of the luminous signal is determined by a weighted average of the analogue signals.

Hence a second detector system, presented here for the first time, has been developed. A beam splitter divides the image of the luminous spot produced by the IEEM phosphor (Fig. 1) into two orthogonal paths. For each optical path the luminous spot is focused into a blade shape by a system of lenses including a cylindrical one. The two cylindrical lenses and consequently the luminous blades along the two paths are mutually orthogonal. Each luminous blade is then intercepted by a linear CCD with 1024 pixels (pixel size 14 μm × 14 μm) placed at 90° respect to the axis of the cylindrical lens. The linear CCDs at the end of the two optical paths are mutually orthogonal and each sensor independently registers one transverse coordinate of the original luminous spot. The coordinate pair is obtained by correlating the frames from the two sensors: a cluster of charge in each linear pixel array frame indicates the presence of a signal and the position of the cluster centroid is taken to be the coordinate of the beam spot along the axis. The repetition rate of this system is set by the frame rate of the linear CCD used, Dalsa CCD IL-P3, that reach frame rates of 37 kHz at a data rate of 40 MHz. Faster linear CCDs are commercially available but their multiple output structure (2 or 4 lines) over-complicates the readout system.

All CCD systems are intrinsically digital: each pixel is an independent detector and the minimum sensitivity is set by the noise level of each pixel; hence the spatial resolution for a given pixel size is essentially independent from the intensity of the luminous spot (once the signal is above the threshold), unlike the PSD. Below we will show that the bi-linear CCD system we developed does not require the image intensifier stage. In addition multiple ion impacts or hot spots are easily identified with a pixel system and coordinate ambiguity can be resolved by associating the coordinates pulses of similar intensity; moreover hot spots can be simply masked.

In bench measurements using an automatic probe station, we determined that the precision on the position measurement of a luminous spot (Gaussian distribution over a cluster of pixels) is slightly better than a pixel: this resolution will be improved by using DSP based readout electronics to maximize the S/N ratio. Considering that in the present configuration 800 pixels for each CCD are used to view a area of 4 cm diameter, the resolution is better than 50 μm on the phosphor screen inside the IEEM (Fig. 2), a factor 2.5 better than the best results obtained with the PSD.

The noise equivalent exposure (NEE) of the employed sensors (Dalsa IL-P3) is equal to 10 pJ/cm^2 which, with a pixel size of 14 μm × 14 μm, corresponds to 41 photons per pixel at $\lambda = 400$ nm. To recognize a three pixel cluster above noise

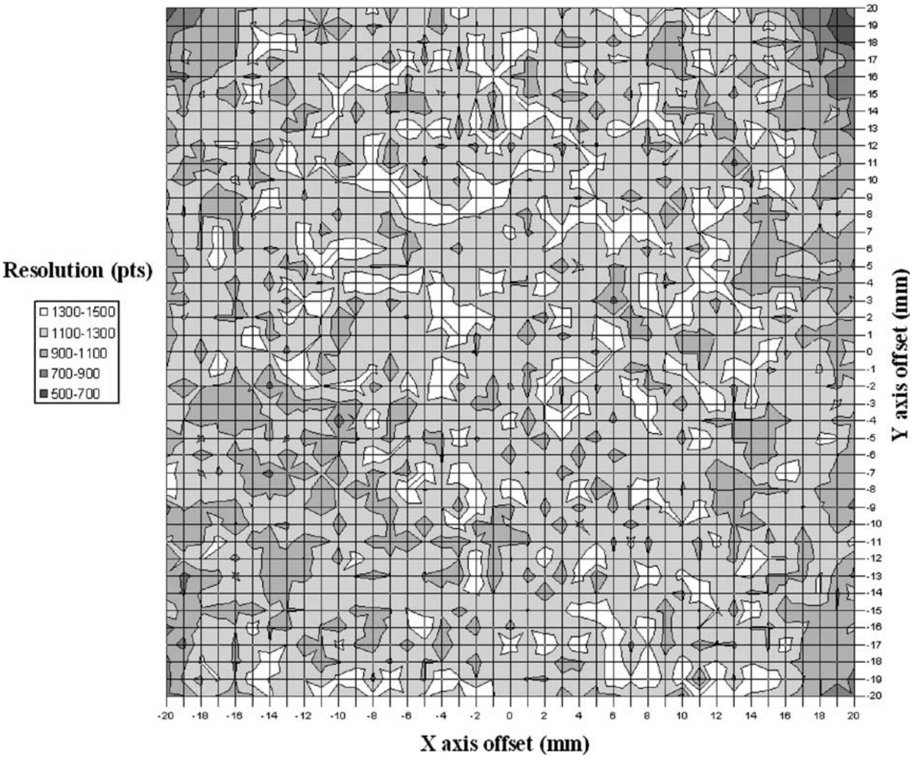

Fig. 2. Device resolution expressed in resolved points. The resolution is very good (better than 800 points) also at the edges of the viewed area.

and determine the position with the desired precision (better than 1 pixel) requires a signal at least 8 times larger, hence about 500 photons. This configuration requires the presence of two independent sensors with a number of optical elements that drops efficiency by a factor 0.25. The use of cylindrical lenses folds in another factor, as the luminous spot is transformed into a blade shape. The fraction intercepted by the CCD varies between 0.1% and 10% depending on the details of the configuration; for the present setup we estimate the interception factor to be 1%. Finally, as already mentioned, the photon collection efficiency from the phosphor at a distance of 25 cm is 1%. This means that at least $500\times4\times100\times100=2\times10^7$ photons are needed to detect a cluster of pixels above noise, a factor 1000 less than those needed for the PSD, and consequently smaller MCP gains (few 10^5) are required. Assuming a gain of 5×10^6, standard working conditions for the two-stack MCP, and a phosphor yield of 60 photons per MCP electron we expect 3×10^8 photons for each secondary electron initiating an MCP avalanche, more than enough to do without the image intensifier.

4. Conclusions

The SIRAD group has developed a novel high lateral resolution opto-electronic detector based on two orthogonal linear CCD sensors This sensor system has a repetition rate of a few 10^4 Hz and allows great flexibility for time resolved ion electron emission microscopy applications such as SEE and IBICC. The IEEM prototype, on standby for installation on the SIRAD beam line, is now working in a PEEM configuration.

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