

# IMPROVED NEAR SURFACE HEAVY IMPURITY DETECTION BY A NOVEL CHARGED PARTICLE ENERGY FILTER TECHNIQUE

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## ABSTRACT

As the typical feature size of silicon integrated circuits, such as in VLSI technology, has become smaller, the surface cleanliness of silicon wafers has become more important. Hence, detection of trace impurities introduced during the processing steps is essential. A novel technique, consisting of a "Charged Particle Energy Filter (CPEF)" used in the path of the scattered helium ions in the conventional Rutherford Backscattering geometry, is proposed and its merits and limitations are discussed. In this technique, an electric field is applied across a pair of plates placed before the detector so that backscattered particles of only a selected energy range go through slits to strike the detector. This can be used to filter out particles from the lighter substrate atoms and thus reduce pulse pileup in the region of the impurity signal. The feasibility of this scheme was studied with silicon wafers implanted with  $1 \times 10^{14}$  and  $1 \times 10^{13}$   $^{54}\text{Fe}/\text{cm}^2$  at an energy of 35 keV, and a 0.5 MeV  $\text{He}^+$  analysis beam. It was found that the backscattered ion signals from the Si atoms can be reduced by more than three orders of magnitude. This suggests the detection limit for contaminants can be improved by at least two orders of magnitude compared to the conventional Rutherford Backscattering technique. This technique can be incorporated in 200-300 kV ion implanters for monitoring of surface contaminants in samples prior to implantation.

## INTRODUCTION

The detection of trace elements in VLSI technology has become increasingly important since small amounts of impurities like Fe or Ni can destroy the device. There are several techniques<sup>1</sup> such as Secondary Ion Mass Spectroscopy (SIMS), Total X-ray Reflection Fluorescence (TXRF) etc., which are sensitive to low level surface contamination. However, there is a need for a non-destructive, quantitative and simple technique. Rutherford Backscattering Spectrometry (RBS), based on elastic scattering of MeV He or H ions, is commonly used for nondestructive, quantitative depth profiling. RBS is especially suited for detection of heavy impurities in light substrates. However, the RBS detection limit for heavy impurities is adversely affected by the underlying background signal, mostly caused by pulse pile-up (chance summing of pulse amplitudes, unresolved in time, from backscattered atoms in the sample matrix). Gunzler et al.<sup>2</sup> have reviewed different experimental techniques to reduce the pileup background. Thin film absorbers, to cut out the lower energy signal and thereby reduce pile up, have been successfully used, however the depth resolution deteriorates because of the inevitable energy broadening caused by straggling in the film. Another ion beam technique being used is backscattering with heavier ions like C or N. Researchers from Sandia National Laboratory<sup>3</sup> have demonstrated a detection limit of  $5 \times 10^9$  at/cm<sup>2</sup> for Ni and Fe in Si, using a 150 keV nitrogen beam in conjunction with a time of flight technique. However, radiation damage produced by heavy ions in the sample and in the surface barrier detector limits its use. Ion channeling is another way to reduce the signal from the substrate and consequently the pulse pileup.

In this study, we present the results of an alternate, inexpensive and simple way to reduce the pulse pileup in a conventional RBS setup, and thereby improve the detection limit of near surface, heavy impurities. An electric field is applied across a pair of plates between the sample and the detector, with the detector staggered with respect to the scattered beam so as to receive the deflected ions in a given energy range. The voltage applied to the plates can be adjusted such that only singly ionized He ions with energies in the range of that corresponding to backscattering from impurities heavier than the substrate are detected. The ions of lower energy corresponding to

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scattering from the lighter substrate atoms, as well as the doubly ionized fraction of the scattered beam are deflected through a greater angle and miss the detector. The undeflected neutral fraction of the scattered beam also does not enter the detector because it is staggered several degrees with respect to the entrance slits defining the scattered beam. Thus, the setup for application of electric field to the scattered beam acts as a "Charged Particle Energy Filter (CPEF)". Due to the suppression of signals from scattering by the abundant substrate atoms, the pulse pileup at higher energies can be drastically reduced. The reduction of the background enables resolution of higher energy signals corresponding to scattering from heavier impurities of low concentration. Ross et al.<sup>4</sup> have applied a similar concept to separate hydrogen and helium charge fractions at forward angles in the Elastic Recoil Detection geometry by means of  $E \times B$  fields.

## EXPERIMENTAL

An incident beam of 500 keV  $\text{He}^+$  is scattered from the sample being analyzed. The CPEF setup is interposed in the path of the scattered beam at  $135^\circ$  in front of a surface barrier detector of  $\sim 11$  mm diameter and 15 keV resolution. Figures 1a and 1b show the scattering schematic and the CPEF setup, respectively. The apparatus consists of two electrode plates and a

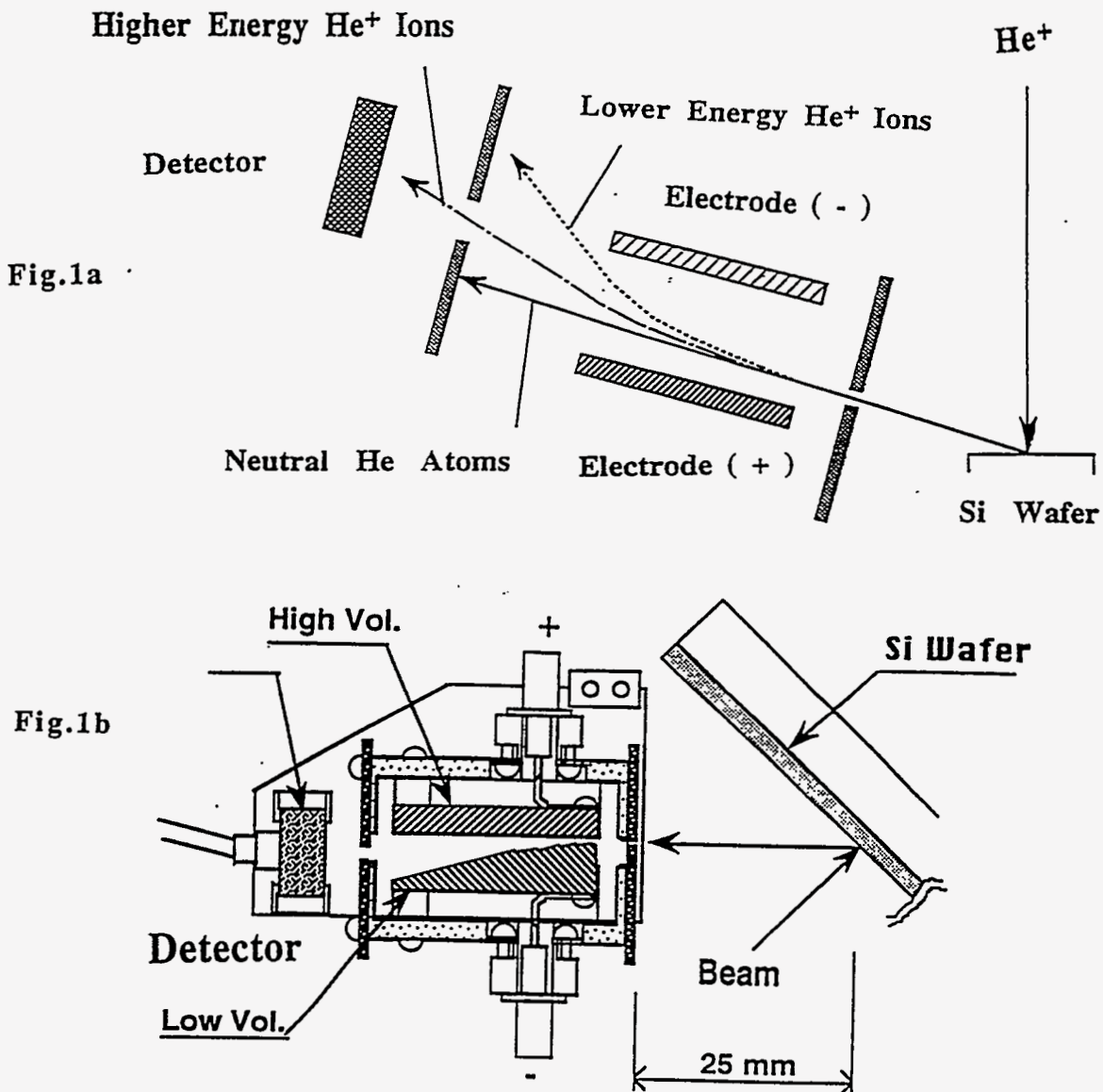


Fig. 1a and 1b Experimental schematic and the CPEF setup.

pair of entrance and exit slits. The shape of the electrodes were carefully designed and fabricated after calculating ion trajectories using the finite element method. The entrance slit (1 mm wide) defines the scattering angle and the energy resolution of the measured energy spectrum. The exit slit, which is adjustable and placed in front of the detector, is staggered with respect to the scattered beam so that the neutral fraction of the backscattered He beam is prevented from reaching the detector. The exit slit width and plate voltage are adjusted to select an energy window around the signal of interest. The doubly charged He ions as well as the lower energy singly ionized He ions are swept away from the detector, while those scattered by impurities heavier than the substrate are allowed to reach the detector. For incident He<sup>+</sup> ions of 500 keV, the maximum energy of the He<sup>+</sup> ions scattered from Si at 135° from Si is 306 keV.

Si samples implanted at liquid nitrogen temperature with 35 keV <sup>54</sup>Fe at doses of 10<sup>13</sup> and 10<sup>14</sup> atoms/cm<sup>2</sup> were employed as targets in the RBS chamber, with the objective of detecting the implanted species near the surface. A voltage, up to a total of 12 kV, was applied across the deflecting plates of the CPEF setup and the optimum position of the exit slit for detection of the Fe signal was experimentally determined.

## RESULTS

With the detector shielded by the slits from the direct scattered beam at 135°, no counts are received by the detector with no deflection field applied. On applying voltage to the plates, one positive and the other negative, the charged components of the scattered beam are deflected by varying amounts. The doubly charged He fraction is deflected more than the singly charged fraction, while the lower energy components within a given charge fraction are deflected more than the higher energy components. Thus, as one increases the plate voltage gradually, one observes those fractions of the scattered beam sequentially being detected. As the higher energy components begin to appear in the detected spectrum, the lower energy components are swept away from the field of view of the detector. The same holds true for the two groups of charge fractions He<sup>+</sup> and He<sup>++</sup>. This behavior is seen clearly in fig. 2, which shows the fractions of He<sup>+</sup> and He<sup>++</sup> as

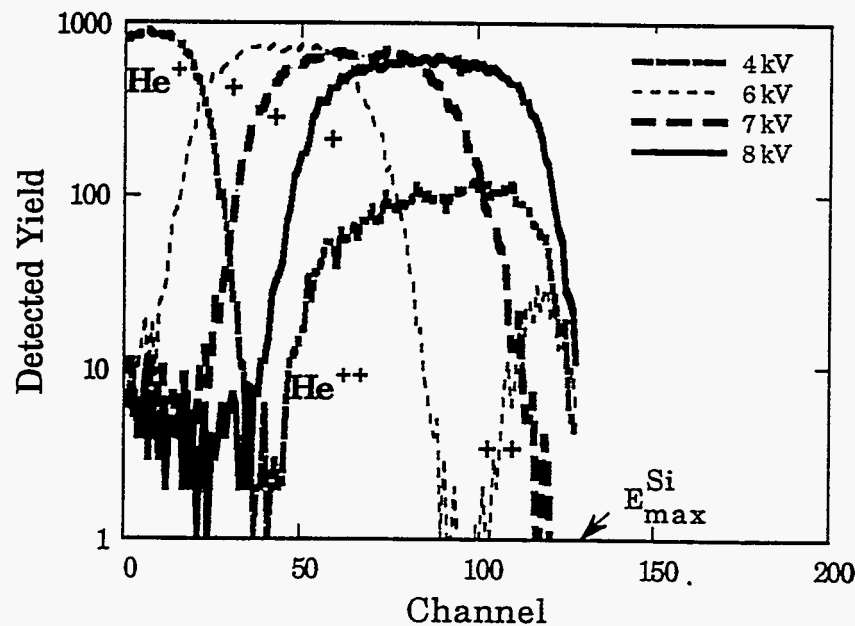


Fig. 2 RBS spectra of backscattered He<sup>+</sup>, He<sup>++</sup> from 0.5 MeV He<sup>+</sup> on Si with different voltages on the CPEF plates

detected for an incident beam of 0.5 MeV He<sup>+</sup> scattered from a Si sample tilted at 6°. The shift of the He<sup>+</sup> and He<sup>++</sup> groups, indicated by + and ++ in the figure, towards higher energy with larger deflection-voltage indicates that as a higher energy component is being detected, the lower energy component is deflected beyond the exit aperture. It may be noted that by the time a deflecting voltage of 6 kV is reached, only a small fraction of He<sup>++</sup> ions are detected, while most of the He<sup>++</sup> fraction is out of the range of detection. Beyond this voltage, all the doubly ionized fraction has been swept out, leaving only the singly ionized component to be detected. The shift of this component towards higher energy, under higher deflection voltage, continues until a maximum energy  $E_{\max}^{\text{Si}} (= K_{\text{Si}} E_0)$  is reached, where  $K_{\text{Si}}$  is the kinematic factor and is the incident beam energy.

The lower energy edge of the group of He<sup>+</sup> ions detected beyond this point keeps shrinking with application of higher deflecting voltages, as can be seen in fig. 3. Again, this is indicative of over-deflection of the increasingly higher energy components, leaving only the highest energy components to be detected. On reaching a deflection voltage of 11.5 kV, only a very small fraction of the signals corresponding to the singly ionized component of the He beam scattered very close to the surface, is left. This, in turn, causes a reduction of the pileup background in the higher energy region beyond  $E_{\max}^{\text{Si}}$ . Once this cutoff point for the Si substrate is determined, the sample of interest containing small impurity concentrations can be analyzed. Fig. 4 shows the detected RBS spectrum in conjunction with the CPEF setup, of a Si sample implanted at liquid nitrogen temperature with  $1 \times 10^{14}$  <sup>54</sup>Fe/cm<sup>2</sup> at 35 keV. The yield from Fe is well above the background and separated from the remainder of the Si signal. It may be noted that the deflection voltage used was such that a small number of the highest energy Si signals were received for detection because of the proximity of the Fe and Si signals at 500 keV incident energy. For impurities somewhat heavier, the Si signals can be completely suppressed, which would help in further reduction of the pileup background.

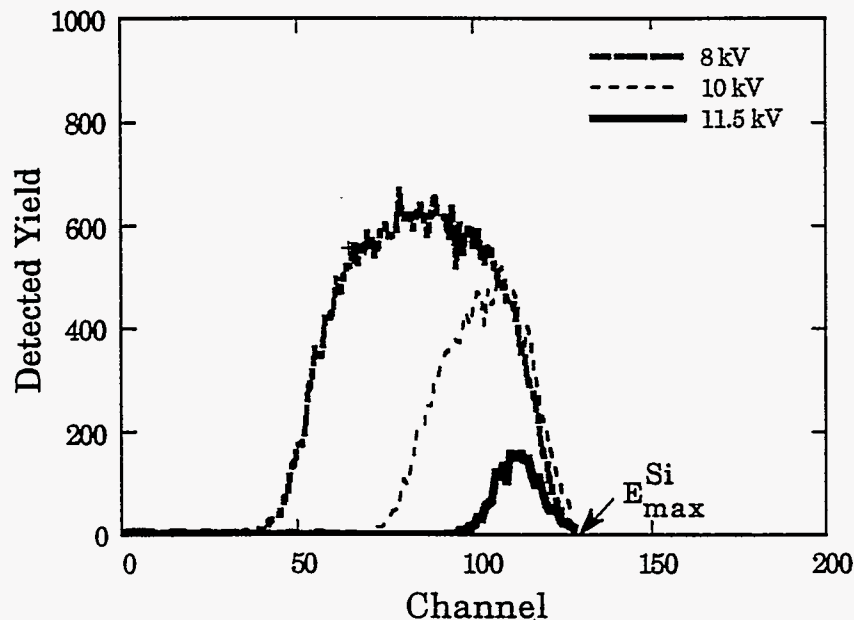


Fig.3 RBS spectra of He<sup>+</sup> fraction scattered from Si with different voltages on CPEF plates

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A sample of Si with  $1 \times 10^{13}$   $^{54}\text{Fe}/\text{cm}^2$  implanted at 35 keV and at liquid nitrogen temperature was also tried with the CPEF technique. The poor counting statistics made detection of  $^{54}\text{Fe}$  difficult, with no clearly pronounced peak above the background. We are currently making efforts to enhance the sensitivity of detection to this limit.

The RBS spectrum of a sample of Si implanted with Ga, analyzed by 500 keV He ions with the CPEF deflector, shown in fig. 5, is compared with the normal undeflected spectrum for scattering at  $135^\circ$ . An improvement in the background, as well as in the peak corresponding to the Ga yield, of better than an order of magnitude is seen, thus making quantitative evaluation of the yields from the heavier impurities more accurate.

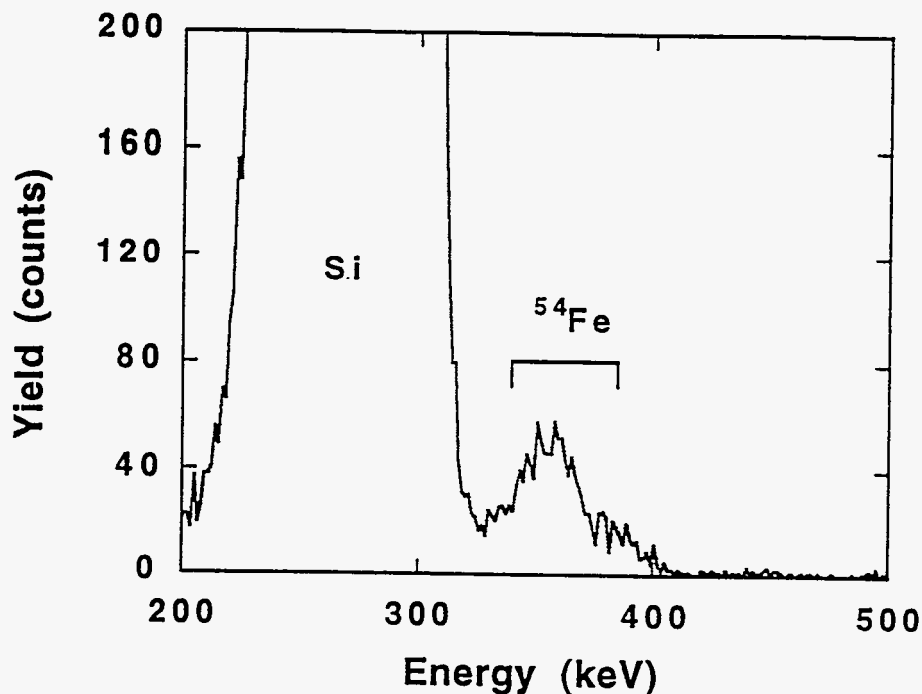


Fig. 4 RBS spectrum of Si implanted with  $1 \times 10^{14}$   $\text{Fe}/\text{cm}^2$  and 12 kV on CPEF plates

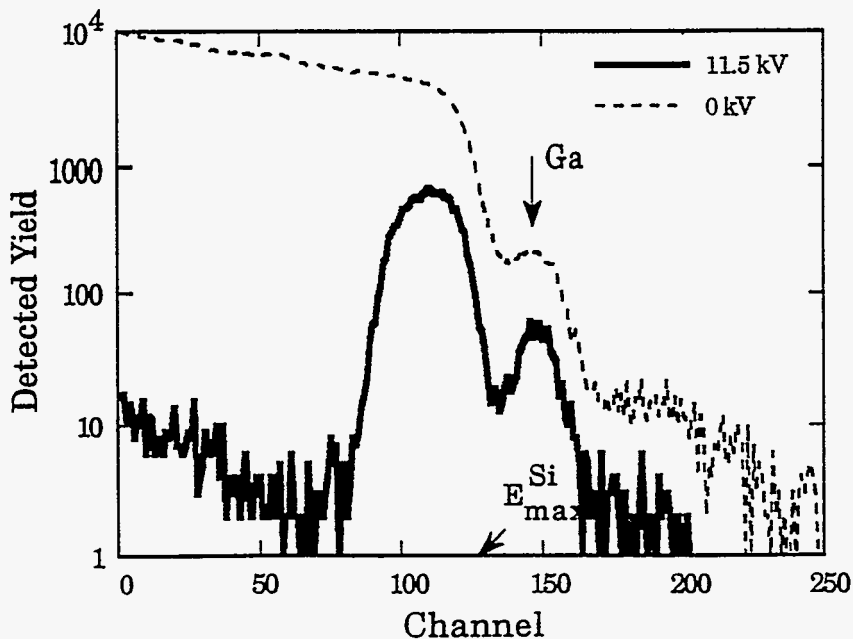


Fig. 5 RBS spectra of Ga implanted Si, with and without deflection voltage to the CPEF plates

## DISCUSSION

The RBS spectra obtained using the CPEF shows that it is possible to control the number of ions scattered from the lighter substrate atoms that reach the detector and hence to reduce the pileup contribution from them. This provides for a lower background in the energy range where the near surface impurities heavier than the substrate contribute to the yield. This favors their detection and one can improve the detection limit by one or two orders of magnitude. In order to quantify the amount of the impurity species present, starting from the detected yields, it is necessary to evaluate the fraction of the singly charged He ions in the total backscattered beam and the effective solid angle of the detector. Although it is known that the final charge state of the exiting ion after traversing a solid material depends only on the last collision with the target atom at the surface, possible dependence of the charge fractions on the target element, the incident ion energy, and angular dependence of the emitted charge fraction may be important.

The choice of low energy incident ions (500 keV He<sup>+</sup>), employed in the present work, was to keep the required deflecting voltages on the plates below 12 kV. In principle, higher deflecting voltages can be employed and the incident energy of the He ions can be raised. This would help in the energy resolution of the impurity elements, but lower Rutherford scattering cross sections at higher energies would result in a lower yield for all elements. Additionally, the variation with energy of the ion stopping power in the sample material is to be taken into account, bearing in mind that the electronic stopping cross section goes through a maximum around 700 keV for Si.

The usefulness of the technique lies in its simplicity and low cost, while preserving the non-destructive feature of RBS analysis with He ions. It can be used on-line with 200 keV ion implanters, where doubly charged He ions of 400 keV can be obtained. The samples can be analyzed by interposition of a CPEF setup to monitor surface or near surface contaminants prior to implantation. While we have demonstrated moderate success, further work is needed to enhance sensitivity in order to compare favorably with TXRF and heavy ion RBS for near surface contaminants. The latter techniques, however, have their own drawbacks, as outlined in the introduction.

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