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APPLICATION OF A DEFLECTOR–DETECTOR SYSTEM FOR RBS ANALYSIS

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In RBS analysis quite often only the high-energy part of the recorded spectrum is of interest, *eg* in the analysis of trace amounts of heavy elements in the near surface region of a light substrate. The speed of data recording and therefore the detection limit of standard RBS analysis is limited by the pulse pileup effects due to the high counting rates of the signal from the thick substrate material. We present a new approach to RBS spectroscopy, which results in a pileup-free high-energy region of the acquired RBS spectrum. This can be done by preventing backscattered low energy particles from hitting the detector. For this purpose an electrostatic deflector-detector system has been developed. The theoretical considerations leading to its proper design are outlined. The first results of the performance of this cost-effective solution are presented.

K e y w o r d s: RBS analysis, heavy elements, nuclear reaction analysis

1 INTRODUCTION

RBS is known to be a very useful analytical technique for the investigation of heavy elements (high Z) on or in light materials (low Z), especially if the high energetic signal of heavy elements is separated from that of the matrix. If very low concentrations of heavy impurities have to be measured, the lowest detection limits are of primary interest. Besides other parameters, the detection sensitivity depends on the signal-to-background ratio in the energy region of interest. If the chosen experimental conditions (projectile, energy, sample elements) exclude the contributions from nuclear reactions, mostly the pileup effects of the signal from the bulk produce the background signal. A low intensity probing beam resulting in a low total count rate can be the solution but, on the other hand, longer time necessary for spectrum collection practically excludes this simple solution. A possibility how to prevent the pileup which was not examined so far is energy filtering of the particles prior to their detection.

An electrostatic filter for blocking low energy particles in Nuclear Reaction Analysis has already been reported [1]. In this work we present a similar concept and the first results of its application in RBS.

2 STATE OF ART

For recording the RBS spectra, two types of spectrometers are used. The first type is the so-called dispersive spectrometer. The advantage of dispersive spectrometers is their high energy resolution and no pileup problem but this is reached at the cost of a low detector solid angle and longer measuring time. Single energy channels are to be measured sequentially, which is a significantly time consuming procedure. The development of a new magnetic spectrometer partially overcoming these disadvantages has recently been reported [2] but due to its complexity it can hardly be used as a low cost option in standard RBS chambers.

The second type a semiconductor detector, detect all particles backscattered to the active area of the detector, in the whole energy range simultaneously. Both neutrals and charged particles are recorded without any distinction. These features could cause problems in some specific applications as discussed below.

Let us consider an RBS measurement of a light substrate with heavy element surface contamination. According to theory in [3], the number of ions N' backscattered from the target atoms to a solid angle $\mathrm{d}\Omega$ is

$$N' \approx \mathrm{d}\Omega Q N \sigma(E_0) \qquad (1)$$

where Q is the total number of incident ions, N is the sheet density of target atoms, $\sigma(E_0)$ is the scattering cross section dependent on ion beam energy E_0.

Similarly, as $\sigma(E_0)$ is proportional to $(Z_1 Z_2/E_0)^2$, the number of detected ions backscattered from the impurity atoms per second (counting rate) N'_{imp} can be expressed as

$$N'_{imp} \approx \Delta\Omega Q' N_{imp} Z_1^2 Z_2^2 E_0^2 \qquad (2)$$

where $\Delta\Omega$ is the detector solid angle; Q' is the beam current; N_{imp} is the number of target impurity atoms per cm^2; Z_1, Z_2 are projectile and impurity atomic numbers.

For the measurement of very low contaminations an improvement of the impurity counting rate is inevitable. This can be achieved by enhancement of one or more terms in equation (2). The most straightforward way is to increase the intensity of the analysing ion beam.

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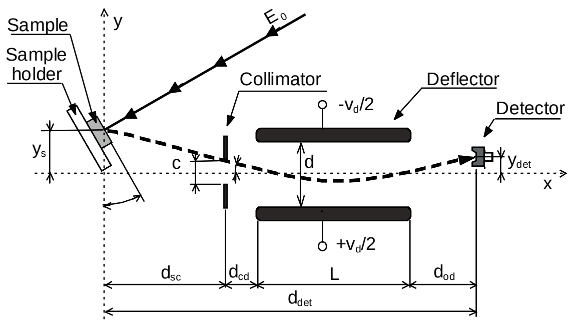

Fig. 1. Schematic of RBS experimental set-up with an electrostatic deflector-detector system. The symbols are explained in text.

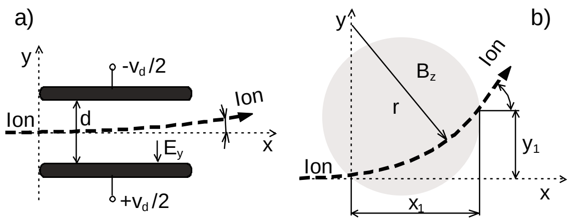

Fig. 2. Charged particle deflection: (a) in electrostatic field, (b) in magnetic field

In this case, however, also the counting rate of the matrix, which is usually several orders of magnitude higher than that of impurity, will be enhanced. This leads directly to the problem of pulse pileup, by which the trace impurity events are superimposed on double- and triple-coincidence signals from the bulk [4]. There are several different approaches how to reduce this limitation.

- Electronic pileup rejection suppresses the pileup background [5-7]. In conjunction with software subtraction of the pileup tail, acceptable count rates of the order of 10^4 counts/s have been achieved. The electronic pulse pair resolution ($10 \div 100$ ns) gives the boundary of the rejection. An extension of the measuring time is the price for dead time expansion.
- excellent sensitivity enhancement has been reached by the detector solid angle enlargement in conjunction with multi-line signal processing and a fast electronic pileup rejection system [4].
- On-request-beam-pulse pileup rejection system used in some PIXE facilities [8-11] can be implemented for RBS as well. Nevertheless, until now no significant improvement has been reached.
- Placing an absorber foil in front of the detector decreases the bulk signal but this method suffers from energy resolution and sensitivity degradation.
- Using heavier analysing beam enhances the impurity count rate and, on the other hand, the matrix backscattering events are suppressed. The major problem of this method is a considerable lowering of the lethal dose for Si-detectors, the worse energy resolution [12], and increasing of the sample damage.

3 DEFLECTOR–DETECTOR SYSTEM AS AN ENERGY DISCRIMINATOR

Let us specify the third type of detection system which presents a fusion of the two types of detectors described in the previous paragraph. In the following it will be referred to as DEFlector-DEtector System (DEFDES).

DEFDES is created by inserting a collimator and an electrostatic or magnetic deflection element between the sample and the standard semiconductor detector (Fig. 1). The energy resolution of the system is given by the detector itself. The deflection element does not serve as a spectrometrical component, although it is used for the energy dispersion of the analysed ions.

The solid angle of DEFDES will be lower than that of a single Si-detector but unlike in dispersive spectrometers the whole energy spectrum in the region of interest is recorded simultaneously.

3.1. Electrostatic deflexion system

Figure 1 shows the sketch of the electrostatic version of such a system. The analysing ion beam with energy E_0 strikes the sample at a spot having y_s as y-coordinate. The entrance of backscattered ions with energy E to the deflecting area is limited by the collimator with slits width c. The slits are located at distance d_{sc} from the sample and d_{cd} from the deflector entrance. The effective length of deflecting plates is expressed by L. The detector is located at a distance d_{od} behind the deflector effective border — *ie* d_{det} far from the sample.

As the beam spot is not a point one and at y direction has a size of b_{sy} and the collimator width is not negligibly small, ions enter the deflector in a certain angle interval. Let us assume that ions are moving just in xy-plane and β represents angle between x-axis and initial trajectory of backscattered ions. In this case the ion y-coordinate y_{det} at detector position can be expressed as

$$y_{det} = \frac{qVL}{2\mathrm{d}E}\,\frac{(L/2)+d_{od}}{\cos^2\beta} + d_{det}\tan\beta + y_s \tag{3}$$

and for a small angle β this can be simplified as

$$y_{det} = \frac{qV_dL}{2\mathrm{d}E}\big((L/2)+d_{od}\big)+d_{det}\beta + y_s \tag{4}$$

where $\pm V_d/2$ are voltages applied to the plates, respectively, and d is the mutual distance of the plates.

3.2. Magnetic deflexion system

Similarly to the previous paragraph, one can treat also the magnetic deflection. Let us substitute the condenser plates in Fig. 1 by a magnetic field of flux density B in $+z$ direction, preserving all other conditions. Analogously to

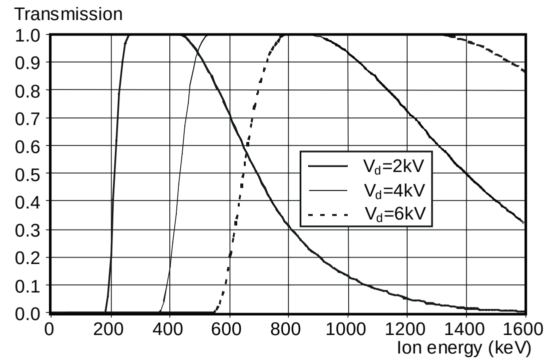

Fig. 3. Theoretical transmission curves of electrostatic DEFDES for various deflecting voltages

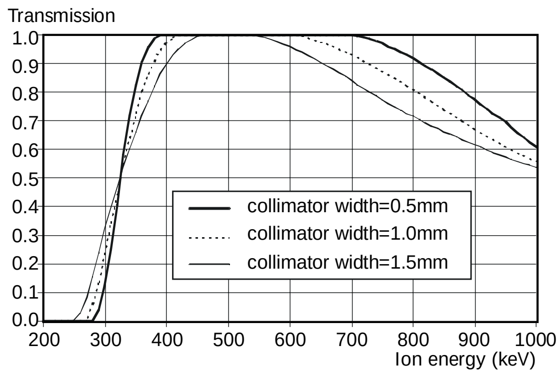

Fig. 4. Theoretical transmission curves of electrostatic DEFDES for different deflector entrance slits apertures, calculated for the deflecting voltage 3 kV

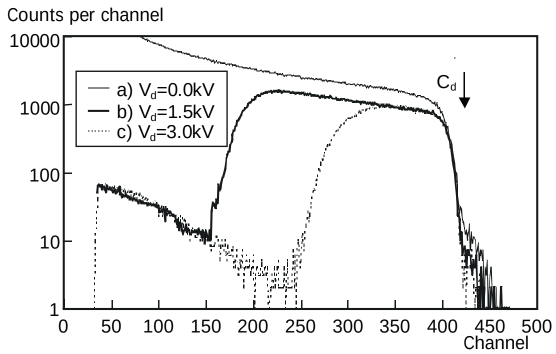

Fig. 5. RBS spectra of Cd sample: (a) – standard, (b) and (c) – with suppression of low-energy backscattered ions.

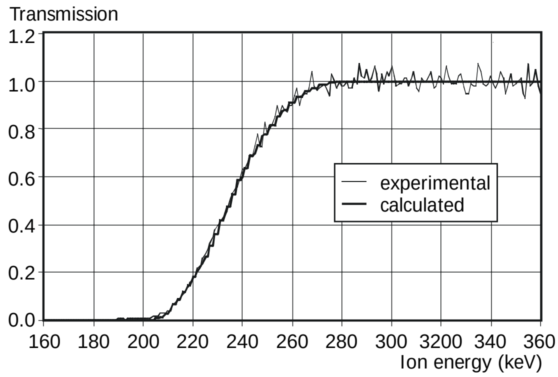

Fig. 6. Example of calculated and experimental DEFDES transmission curves

equations (3) and (4) the ion y-coordinate at detector position for a small angle β can be derived

$$y_{det} = \frac{qe}{\sqrt{8m}} \frac{B}{\sqrt{E}} L(L + 2d_{od}) + d_{det}\beta + y_s \qquad (5)$$

where e is the elementary charge.

This expression for He ions and energy E in [keV] yields

$$y_{det} = 54.916 \frac{qBL}{\sqrt{E}} (L + 2d_{od}) + d_{det}\beta + y_s \,. \qquad (6)$$

3.3 DEFDES design and characteristics

Considering the dimensions and the manufacturing simplicity, the electrostatic version of deflexion element was chosen. Following the equations (3), (4) one can describe the motion of an ion between the sample and the detector. Concerning the suppression of the neutral fraction which dominates at low energies of the backscattered particles, a slight DEFDES misalignment must prevent a direct impact of neutrals on the detector. A sharp edge of the beam spot and its parallelism with the deflector entrance collimator are also required.

Dimensions of the DEFDES prototype (Fig. 1) given in mm were as follows: $L = 90$, $d = 4.1$, $b_{sy} = 2$, $c = 0.7$, $y_s = 2.5$, $d_{sc} = 160$, $d_{cd} = 10$, $d_{od} = 15$, $d_{det} = 275$.

Energy dependence of the throughput — the transmission curve — is the main characteristic of the DEFDES. With an increasing energy the transmission curve rises from zero to 1 where it persists to form a plateau — full transmission region (FTR). After the plateau, the curve declines again to zero. The rising of the electrostatic version is steeper than that of the magnetic equivalent.

The location of the FTR on the energy scale can be controlled via adjustment of the deflecting voltage V_d (see Fig. 3 and Fig. 5). The influence of the variation of the beam spot width on the transmission curve is similar as the influence of the collimator aperture presented in Fig. 4. The enlargement of any of the mentioned parameters causes a reduction of the FTR size. In our configuration the deflecting voltage $V_d = 6$ kV corresponds to the FTR from 660 keV to 985 keV for singly charged He ions.

4 EXPERIMENTAL

The RBS measurements for the electrostatic DEFDES testing were made with Cd-bulk and Pb-implanted Si samples. The experiments were performed in 1 MV cascade accelerator facility at the Slovak University of Technology [13]. The 500 keV $^4He^+$ ion beam with a current of 80÷200 nA was focused to a spot of 2×5 mm^2, yielding

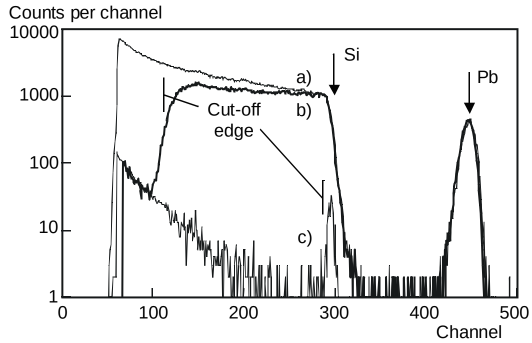

Fig. 7. 500 keV $^4He^{1+}$ RBS spectra of 10^{15} at/cm^2 shallow Pb implant in Si: (a) standard Si-detector spectrum; (b) DEFDES spectrum with suppressed low energy region (deflecting voltage $V_d = 1$ kV); (c) DEFDES spectrum with almost complete Si signal suppression ($V_d = 3$ kV).

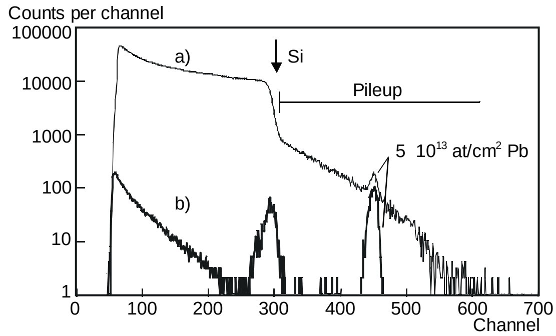

Fig. 8. Pileup elimination via DEFDES. 500 keV $^4He^{1+}$ RBS spectra of 5×10^{13} at/cm^2 shallow Pb implant in Si. The count rate of the Pb signal was identical in both cases: (a) standard RBS; (b) RBS with DEFDES, deflecting voltage $V_d = 3$ kV.

the current density of $0.8 \div 2\,\mu$A/cm^2. The RBS spectra were measured in the multipurpose experimental chamber using the 12 keV FWHM 25 mm^2 Si implanted detector [14] or 10 keV FWHM 100 mm^2 Hamamatsu detector at a backscattering angle of 135°. The solid angle of the DEFDES unit with the latter detector was 0.15 msr. The deflection voltage was adjustable up to 5 kV. Vacuum during the measurements was kept below 5×10^{-5} Pa. ORTEC 142A and ORTEC 572 preamplifier and amplifier, respectively, processed the signal from the detector. No electronic pileup suppression was used.

The Si samples were prepared in Max-Planck-Institut für Kernphysik, Heidelberg by 2 keV Pb$^+$ implantation with a dose of $10^{13} \div 10^{15}$ at/cm^2.

5 RESULTS AND DISCUSSION

The spectra of the Cd sample (Fig. 5) were used to derive the DEFDES transmission curve (Fig. 6). The real goal of the DEFDES application — suppression of the Si bulk signal (line a) — is shown in Fig. 7. The cut-off edges at 100 keV (line b) and 300 keV (line c) were achieved by $V_d = 1$ and 3 kV, respectively. In the latter case almost the entire Si signal is suppressed. At the low energy region of all collected DEFDES RBS spectra an insignificant background signal remained, originating probably from the scattering at the deflector plates.

Practical application of the DEFDES is demonstrated in Fig. 8. During the acquisition of the standard RBS spectrum of a Si sample implanted with 5×10^{13} at/cm^2 of Pb (line a), the total counting rate was higher than 10^4 cps. The impurity signal on the corresponding spectrum is superimposed on a high energy pileup tail. After the Si bulk signal elimination (line b) the total counting rate was radically decreased down to the level of the counting rate of the Pb signal. As a consequence, no pileup events can be found in the collected spectrum.

As demonstrated in this example, DEFDES can be an alternative tool for pileup suppression in RBS analysis. The consequences of its utilisation are discussed in the sequel.

- **RBS applicability:** The sharp rise of the DEFDES transmission curve and the wide FTR allow an effective RBS application. The bending electrostatic field does not change the energy of ions but modifies their direction. The variance of the impact angle causes a shift in the detected energy (due to the detector surface dead layer) but this effect is lower than the energy shift of the standard RBS experimental set up caused by a finite detector solid angle. No RBS spectra distortion in the FTR region has been observed (see superposition of Pb peaks from several measurements in Fig. 7).
- **Pileup elimination:** The total counting rate can be reduced by at least $4 \div 5$ orders of magnitude. In combination with up to date electronic pileup suppression, the analysing beam current can be enhanced by the same factor. This enhancement is, however, restricted by a resistance of the sample to the beam. The realistic values of up to $100\,\mu$A/cm^2 [15, 16] can be applied even without the electronic pileup rejection systems.
- **Detector life time enhancement:** An enormous prolongation of the detector life time can be expected as the total number of particles that actually hit the detector is significantly reduced. This could be of interest in heavy ion beam backscattering spectrometry.
- **Solid angle reduction:** A drawback of the DEFDES application is a reduction of the detection solid angle by a factor of $5 \div 10$ with respect to a single solid state detector.
- **Charge state consequences:** As the DEFDES is a charge sensitive system, when applied to ^{4}He RBS, the following must be taken into account:

If $E_o < 1$ MeV, the He^{1+} fraction dominates and is also of primary interest. We require the trace element signal to be in the FTR of the 1+ fraction. Let us suppose that the cut-off edge for matrix suppression is about $0.65 \times E_o$ (Si kinematic factor $k_{\rm Si} \approx 0.6$). As the cut-off energy of 2+ charge state particle $E^{2+}_{\text{cut-off}}$ is twice the

$E^{1+}_{\text{cut-off}}$, FTR of 2+ fraction will be at energies over E_o, *ie* He^{2+} fraction will not be detected.

If $E^{1+}_{\text{cut-off}} < 0.5 \times E_o$, which can be the case when *eg* only the carbon signal has to be cut off, then $E^{2+}_{\text{cut-off}} < E_o$. One should be careful in this case, as superposition of He^{1+} and He^{2+} signals in the energy interval from $E^{2+}_{\text{cut-off}}$ to E_o takes place. However, this is important only when analysing ultra-thin layers, as for random incidence of < 2 MeV He^{2+} ions on solid surfaces the depth for reaching the equilibrium charge state is of the order of $\sim$ nm [17].

6 SUMMARY

The application of a deflector-detector system to remove the low energy part of RBS spectra can be an alternative way to pulse pileup elimination. The ratio of the impurity counting rate to the total one was in our case increased by 4 orders of magnitude. As a result, an improvement of the effective sensitivity of RBS analysis in some specific cases can be expected. The spectra recorded in the system full transmission region are not distorted and only charge state correction must be performed to obtain the standard RBS spectra.

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