Accelerators in Applied Research and Technology
– A report on the First European Conference, Frankfurt A/M, September 1989

Hans Henrik Andersen
Physics Laboratory
H.C. Ørsted Institute, University of Copenhagen
Universitetsparken 5 , DK–2100 Copenhagen Ø, Denmark

ABSTRACT
The first European Conference on Accelerators in Applied Research and Technology (ECAART 1) is reported upon through discussion of a number of examples of the papers presented in the conference. The main topics were Ion Beam Analysis, Ion Beam Modification of Materials and Development of Accelerators for Industrial Applications.

INTRODUCTION

Particle accelerators, as originally developed for nuclear and particle physics experiments have found widespread use in a wide range of other fields of physics as well as for applications in technology and medicine. Many elements of the technological development of accelerators came simultaneously from the electronics industry and resulted in the emergence of the transmission electron microscope nearly sixty years ago. This instrument may be considered a prototype of an applied accelerator, these days to such a degree of self–evidence that it is not even mentioned when applications of accelerators are discussed. In the 1950's a new line of development started. Targets for nuclear–physics experiments were prepared by ion–implantation in solids. On the one hand such a development demanded very versatile ion sources utilizing sophisticated knowledge of atomic physics. On the other hand, the availability of low–energy accelerators delivering beams of virtually any element in the periodic system made a very broad range study of atomic–collision processes possible and created the background for ion implantation and analytical uses of accelerators. This development was described in some detail by K. Bethge at the previous EPAC in Rome (1). In the United States a series of International Accelerator Conferences have been running for many years. The EPAC conferences were modelled on these. Similarly, J. Duggan have since the early 1970's organized a biannual series of conferences in Denton, Texas known as the "Denton Conferences" or "Small–Accelerator Conferences". These events have grown very large and have their proceedings published in Nuclear Instruments and Methods, Section B (2). In spite of the existence of a number of more narrowly topical conferences, some of which shall be mentioned below, a need was felt for a similar forum, where European scientists working with applications of accelerators could meet with interested parties from industry and researchers from fields outside the physical sciences but making use of accelerator technology. Hence the first European Conference on Accelerators in Applied Research and Technology was organized in Frankfurt am Main, FRG on September 4–9, 1989 and attended by approximately 230 participants listening to 23 plenary talks and scrutinizing more than 100 detailed contributions presented mainly as posters. The proceedings of the conference have appeared, as with the Denton Conferences, in Nuclear Instruments and Methods, Section B, in May 1990 (3). As the proceedings are available for obtaining detailed information, it is felt more relevant to illustrate the topics treated at the conference by some examples rather than presenting a more detailed listing of most of the presentations. As the field is a rather mature one, such an approach is particularly adequate. Few totally new results will appear but new data adds continously to the knowledge. Examples are therefore mostly chosen for their ability to illustrate trends.

The topics of the conference may be grouped under the headings Analysis, Materials Modification and Accelerator Development and examples will be given within each group. A number of papers had elements within different groups. Quite often papers mainly concerned with analysis actually investigated samples made by ion implantation, development of nuclear microprobes and synchrotron radiation facilities were made to create analytical possibilities and papers often gave such applications as illustrations et cetera.

ANALYSIS

Ion Beam Analysis may be defined very broadly as the techniques utilizing for analytical purposes the secondary radiation emitted when samples are bombarded with energetic charged particles. Usually, only prompt emission is considered under that heading, i.e. charged–particle activation analysis is not included. Otherwise, electrons as primaries may be included hence embracing techniques like electron microprobe and Auger analysis. Similarly, x–ray fluorescence, particularly induced through synchrotron radiation, is often treated under such a heading. The strictly ion induced techniques have their own conference series like the Ion Beam Analysis (IBA) conferences (4) and conferences on Proton Induced x–ray Emission (PIXE) (5). Recently regular textbooks have also appeared (6,7,8). A prerequisite for performing IBA is that cross sections and energy loss (stopping power) data are available. Such information was presented only to a very limited extent in Frankfurt. Apart from at the abovementioned conferences (4,5), particularly energy–loss information will to a large extent be presented at the biannual conference on Atomic Collisions in Solids (9).

The first example will be drawn from a series of papers from the Göttingen group (10,11,12). The surface hardness of stainless steels and aluminium–magnesium alloys may be improved by application of a thin layer of titanium or titanium nitride. It is often a problem to get sufficient adhesion between such an applied layer and the substrate. One method to improve adhesion is through bombardment with heavy ions of a range somewhat larger than the film thickness. Radiation damage at the interface gives rise to an atomic mixing both through direct recoil implantation and through radiation–enhanced diffusion. Here, 30–300 nm Ti and TiN films were irradiated with 80–700 keV Ar, Kr and Xe ions at doses up to 2.1 x 10^{17} ions/cm^2. One question is here what happens to the nitrogen in the film. This may be probed by the resonant nuclear reaction $^{15}N(p,\alpha\gamma)^{12}C$ at 429.57 keV. Protons impinging at the resonant energy will induce the reaction at the target surface. If they impinge at higher energies, their energy loss will ensure that they reach the resonant energy at larger depths. Hence, knowing the stopping power allows to convert an energy scale to a depth scale. An example is shown in Fig. 1. It is seen that the front edge, which is considerably steeper than the back edge, remains constant during Kr bombardment. The back edge is less steep due to energy straggling of the probing beam. For larger Kr–doses, the back edge is becoming even more smeared due to the sought–for ion beam mixing at the interface. Simultaneously, the total layer thickness decreases due

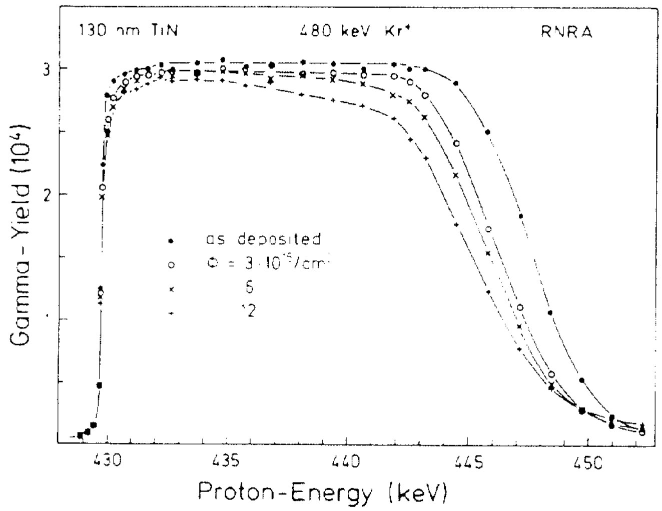

Fig. 1. Resonant nuclear reaction scan of the depth distribution of ^{15}N in a 130 nm TiN film on stainless steel after bombardment with 3,6, and 12 times 10^{16} 480 keV Kr ions per cm^2. (From ref. 3, page 10).

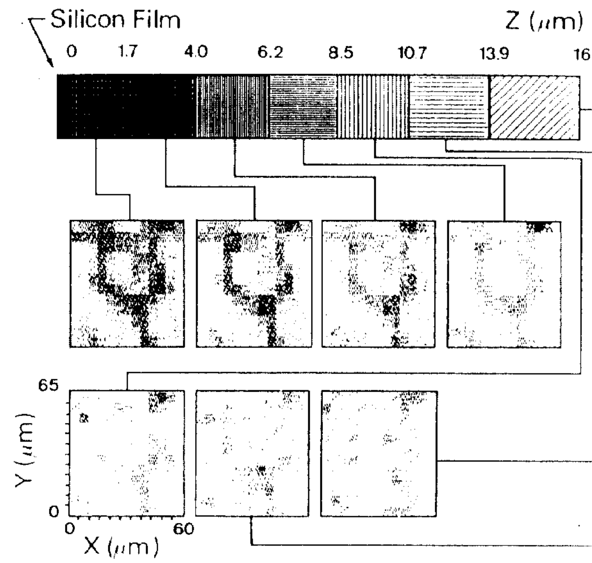

Fig.2. Three dimensional distribution of silicon in gold after diffusion at 400^0C, as profiled with a microfocused deuteron beam by the ^{28}Si (d,p) ^{29}Si reaction (From ref. 14).

to krypton sputtering of the film. The sputtering yield may be deduced from the decrease in the total number of N atoms with heavy ion bombardment. Similar information may also be obtained from proton–induced x–ray emission (PIXE) of Ti (ref. 12) or Rutherford Back Scattering (RBS) analysis of the imbedded heavy–projectile atoms (ref. 11). Sputtering data are important to estimate the maximum allowable dose for ion beam mixing of a thin film. These measurements nicely ilustrates the interplay between ion beam analysis and ion beam modification studies.

The same resonance reaction may be used for hydrogen depth profilling if a ^{15}N probing beam is utilized. This is illustrated by a study of electrochromic effects (13). Electrochromic multilayer systems are configurations using the electrochromic effect for controlling reflectance or transmittance of optical devices. The absorbance of these systems may be changed by applying an external voltage of the order of 1 V. Either WO_3 or NiO_x is used as the coloring material for instance for so–called "smart windows", where the transmittance of sunlight may be regulated according to the time of the day or year. The origin of the effect is usually sought in a mechanism, where the oxidation state of the metal ion in the electrochromic layer is changed through injection of hydrogen in the metal oxide. Hydrogen profiling of the systems yielded a satisfactory agreement with model calculations for NiO_x but not for WO_3, where the concentration changes were less than expected. If the probing beam is focussed sufficiently well, three–dimensional information may be obtained. This is illustrated by a study by Mathot and Demortier (14) of grainboundary diffusion of silicon in gold. 100 nm silicon films were deposited on gold foils maintained at 400^0C to allow diffusion. The silicon is profiled with a deuteron beam utilizing the exoenergetic ^{28}Si (d,p) ^{29}Si reaction. The deuteron beam was focused to 5 μm and the sample moved over the focused spot. Energy analysis of the protons emitted in the forward direction gave depth information as displayed in Fig. 2. It is clearly seen that the silicon penetrates along two–dimensional features in the underlying 16 μm gold foil.

The channeling phenomenon, i.e. the decrease in small–impact parameter processes when the probing beam is incident along close–packed directions in single crystals may be utilized for a number of purposes. Particularly the reorganization of surface structures and lattice vibrations as well at the surface as in the bulk may be studied. The most spectacular recent results of this sort of research is the investigation by the Argonne group of lattice vibrations in $YBa_2Cu_3O_{7-x}$ crystals (15). At the superconducting transition temperature a step in the latiice vibrations of the Cu–O (but not in the Y–Ba) strings is found indicating some transition to a softer vibration mode. This result gives important clues to the mechanism of superconductivity in high–T_c ceramic materials. Although the result was not formally presented (but certainly discussed) at the Frankfurt conference, it is mentioned here to indicate the power of the RBS–channeling investigations.'

Another important application of channeling techniques if for the study of strain in semiconductor heterostructures grown by Molecular Beam Epitaxy (MBE). At the conference the Philips group presented such studies on $Si/Si_{1-x}Ge_x/Si$ targets (16). The difference in lattice constant between the two materials gives rise to strain (deformation from a cubic lattice to a tetragonal one) that may be detected by channeling. Interdiffusion relaxes the strain and hence such diffusion effects may also be studied by the channeling effect. Such investigations demand very high resolution angular scans to be performed. The obtained results show good agreement with Monte Carlo Simulations of the probing–beam behaviour.

High–precision analysis demands all cross sections as well as the detector geometry and efficiency to be known very accurately. Further, it is not sufficient that currents may be measured reproducibly, absolute precision is demanded. A large amount of such difficulties may be circumvented if good standards are available. The CEC Geel laboratories have invested a considerable effort in preparing and characterizing such standards (17). They characterized e.g. thin ($10 \mu g/cm^2$) evaporated gold layers. The average thickness remained constant (as determined by weighing) within 0.03% over a period of 15 years. Fig. 3 illustrates, however, that if such samples are used for standards for RBS measurements, local variations in the target thickness may give rise to a further uncertainty of 0.6%. As the ratio between RBS cross sections of different target elements is known with high precision, such standards do not only apply to specific target materials.

Ion beam analysis demands apart from accelerators also detectors. For RBS analysis, energy–dispersive detectors are necessary. These have either a relatively poor energy

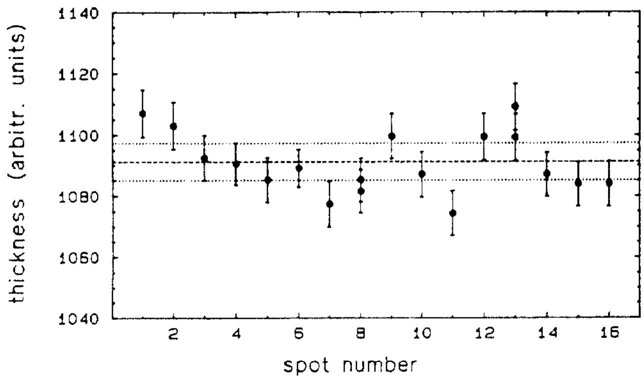

Fig. 3. Local thickness variation of gold layers approximately 10 $\mu g/cm^2$ in thickness, determined by RBS analysis. The spot size is 2 mm in diameter, the distance between spots 12 mm. (From ref. 17).

resolution (semiconductor surface–barrier detectors) or cover a very small solid angle (electrostatic or magnetic spectrometers). It is hence very exciting that bolorimetric particle detectors show signs of being able to reach resolutions substantially better than those of semiconductor ones. Such detectors were first used for charged–particle detection by Coron et.al. (18). Although the energy resolution was somewhat poorer than the surface barrier detectors, a very high resolution was predicted. This was later shown hardly to be theoretically feasible (19) but an energy resolution of the order of 1 keV for MeV protons and helium ions should still be feasible. Such detectors would mean a substantiable increase in the depth resolution of RBS. At the conference, the Jülich group (20) presented results for as well a silicon bolometer as for a copper bolometer with a silicon thermometer. The detector is placed at the very low temperature of 0.15 K, where heat capacities are small and the sensitivity of semiconductor thermometers very high. Fig. 4 shows an RBS spectrum from a Ta/Cr sandwich on an Si backing.

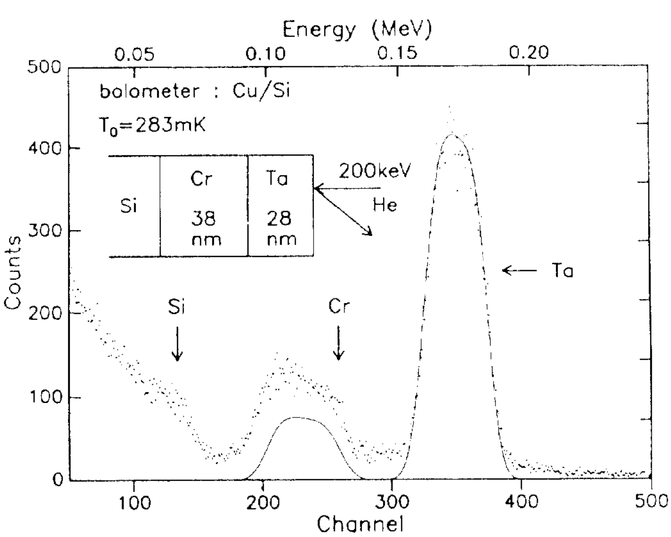

Fig. 4. RBS spectrum of a 200 keV He beam scattered from a Ta/Cr sandwich on an Si backing. The spectrum was measured with a copper on silicon bolometer at 0.28 K. The full line represents a model simulation of the energy spectrum (From ref. 20).

The model fit indicates a resolution of 9.5 keV. With the Si bolometer a resolution of 8.0 keV was reached. For hydrogen, the energy resolution was similar but for 320 keV boron ions a substantial deterioration was found in agreement with theoretical expectations (19).

Walter Kutchera (21) reviewed recent developments in accelerator mass spectrometry, which offers the promise of measuring stable/radioactive isotope abundance ratios of the order of 10^{16}. The most wellknown isotope studied by such techniques is ^{14}C. Routine dating of very small samples have been made for more than 10 years. Nevertheless, the recent dating (22) to medieval times of the shroud of Turin was a media event. Also ^{10}Be has been used extensively particularly for geophysical applications such as plate tectonics studies. Other isotopes used are ^{26}Al, ^{36}Cl, ^{41}Ca and ^{129}I. This is only a very small selection of the more than 100 isotopes with half lives longer than 1 year and lots of possibilities certainly lie ahead. Also this analytical technique has its own conference series (23).

ION BEAM MODIFICATION OF MATERIALS

As has already been mentioned above, relatively low energy ion beams may be used to modify the properties of near–surface layers of materials (24). The well–established application is for ion implantation in semiconductors for routine fabrication of VLSI circuits. Dopants like boron or phosphorus are implanted with energies up to a few hundred keV. A more recent development is the use of higher (up to 1 MeV) implants, particularly of light ions like carbon and nitrogen to form buried compound layers of e.g. SiC, SiO_2 or SiN. Such studies were reported upon by K.G. Stephens (25). An example of evidence for formation of such a layer is shown in Fig. 5. 200 keV carbon is implanted into silicon. It is seen

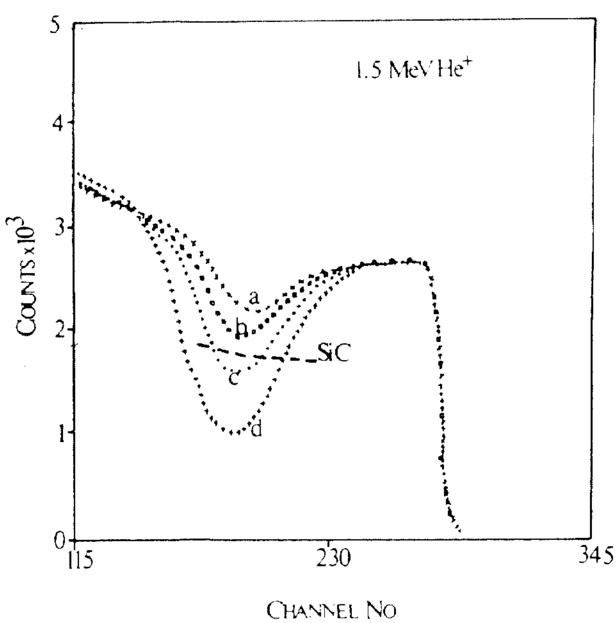

Fig. 5. Non–aligned RBS spectra for Si specimens implanted at 200 keV with 3.5 x 10^{17} C/cm^2 (a) up to 1.9 x 10^{18} C/cm^2 (d). (From ref. 25).

that stoichiometric SiC is not formed, but this may be achieved through 20 hours annealing at 1300^0C. Rather high implantation fluences are needed in contrast to semiconductor doping. Even larger fluences are necessary to obtain significant wear and corrosion improvements of metal surfaces as reported by one of the pioneers of such applications, G. Dearnaley from Harwell (26). Particularly, very high fluences of nitrogen and coverages of large areas are necessary. Hence the need for special high–current machines as described below.

A totally different sort of materials modification was treated by D.J.S. Findlay from Harwell (27). He discussed applications of photonuclear reactions in general and the necessary equipment to supply the photon fluxes. A particularly interesting application is the incineration of fission products (through (γ,f) reactions) and actinides in radioactive waste (through (γ,n) reactions). Although sufficient photon fluxes are not yet available, very interesting perspectives are raised by such proposals.

NEW BEAMS AND ACCELERATORS

One of the most exciting developments in recent years on the equipment side is the emergence of the ion microprobe: Ion beams are focused to submicron sizes and used for analytical, lithographical or implantation–writing purposes. The principle is illustrated in Fig. 6. Obviously, a high–brightness ion source will be needed to achieve sufficient illumination of the target.

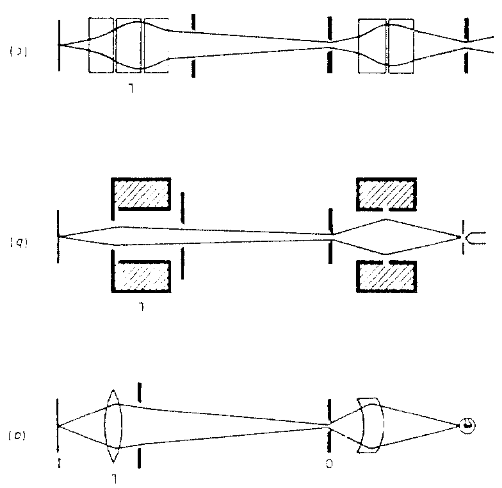

Fig. 6. A comparison between light (a) electron (b) and ion (c) focusing systems. In each case the radiation emerges from a source to the left and is concentrated on a defining aperture by a condenser system. The focusing devices used are glass lenses for light, magnetic solenoid lenses for electrons and quadrupole lenses for ions. (From ref. 27).

Note that solenoid lenses, like those used in the transmission–electron microscope, are not sufficiently strong to focus an MeV ion beam. Kurt Traxel from Heidelberg (28) discussed the technical problems involved, particularly the aberration of lens systems, the construction of the object aperture and the position and construction of scanning systems, while Geoff Grime and Frank Watt (29), among others, illustrated the state–of–art in application of the instruments. The consensus was that useful beams with a size of 0.5 μm have now been achieved.

Another exciting development is taking place with the appearance of well–defined e^+–beams of low intensity (30). For standard measurements of positron lifetimes in solids, the start signal for the clock is the gamma quantum emitted form the source together with the positron. As the detection efficiency for these gammas is very low, lots of spurious coincidences occur. If, instead, the positrons are focussed and accelerated to some MeV, they may be sent through a thin foil, where emitted secondary electrons are used as the start signal. With such a system spurious coincidences may to a large extent be avoided and the time resolution be pressed to 100 ps.

Large–current accelerators are most conveniently built as AC machines. R.W. Thomae (31) discussed RFQ machines and the MEQUALAC concept shown in Fig. 7. This is a

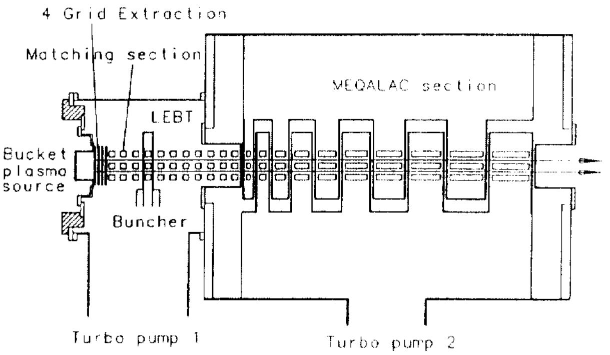

Fig. 7. The experimental setup of the MEQUALAC experiment. Four N^+ beams are extracted from amulticusp bucket source and transported by the bunching system to the 25 MHz cavitiestors in which the particles are accelerated to 1 MeV.

multibeam system, here shown in a four–beam version. The acceleration section is a linac with static quadrupole transverse focusing. Lots of parallel beams may be assembled but in the present four–beam version, 6 mA nitrogen at 1 MeV may be achieved. Such systems will be necessary to make surface treatments of large machine parts as mentioned above.

CONCLUSIONS

The first ECAART succeded in bringing together a substantial fraction of the European scientists using accelerators for applied research. It is expected that the second conference, to take place in Frankfurt in September 1991, will draw substantially more participants, hopefully with a stronger representation of users from the industrial side. It is further expected that ion beam analysis will have a less prominent role than at the first conference and that work with electron beams will be more strongly represented.

REFERENCES

1. K. Bethge in S. Tazzari (edt.): Proc. European Accelerator Conference (World Scientific, Singapore, 1989) p. 158.

2. For the latest issue see J.L. Duggan and I.L. Morgan (eds.): Applications of Accelerators in Research and Industry '88. (North–Holland, Amsterdam, 1989). (Nuclear Instruments and Methods Vol. B 40/41, 1989).

3. K. Bethge, F. Rauch, P. Misaelides (eds.): Accelerators in Applied Research and Technology (North–Holland, Amsterdam, 1990) (Nuclear Instruments and Methods Vol. B50, 1990).

4. For the latest conference see J.F. Ziegler, P.J. Scanlon, W.A. Lanford, and J.L. Duggan (eds.): Ion Beam Analysis 9 (North–Holland, Amsterdam, 1990). (Nuclear Instruments and Methods Vol. B45, 1990).

5. For the latest conference see R.D. Vis (edt.): Particle Induced x–Ray Emission and Its Analytical Applications 5. (North–Holland, Amsterdam, 1990). (Nuclear Instruments and Methods Vol. B49, 1990).

6. L.C. Feldman and J.W. Mayer: Fundamentals of Surface and Thin Film Analysis (North–Holland, Amsterdam, 1986).

7. J.R. Bird and J.S. Williams: Ion Beams for Materials Analysis. (Academic Press Australia, Sydney, 1989).

8. S.A.E. Johansson and J.L.Campbell: PIXE–Novel Technique for Elemental Analysis (Wiley, Chichester, 1988).

9. For the proceedings of the latest conference see F. Besenbacher, J.U. Andersen and A.H. Sørensen (eds.): Atomic Collisions in Solids 13 (North–Holland, Amsterdam, 1990) (Nuclear Instruments and Methods, Vol. B48, 1990).

10. K.P. Liep, W. Bolse, Th. Corts, W. Müller, Th. Osipowicz and Th. Weber; Nuclear Instruments and Methods B50 (1990) 10 (Ref. 3, p. 10).

11. Th. Weber, W. Bolse, and K.P. Lieb; Nuclear Instruments and Methods B50 (1990) 95 (Ref. 3, p. 95).

12. T. Osipowicz, Th. Corts, K.P. Lieb and F.J. Bergmeister; Nuclear Instruments and Methods B50 (1990) 238 (Ref. 3, p. 238).

13. W. Wagner, F. Rauch, C. Othermann, and K. Bange; Nuclear Instruments and Methods B50 (1990) 27 (Ref. 3, p. 27).

14. S. Mathot and G. Demortier; Nuclear Instruments and Methods B50 (1990) 52 (Ref. 3, p. 52).

15. L.E. Rehn, R.P. Sharma, P.M. Baldo, and J.Z. Liu; Nuclear Instruments and Methods B48 (1990) 200 (Ref. 9, p. 200).

16. L. van Ijzendoorn, G.F.A. van de Walle, A.A. van Gorkum, A.M. Theunissen, R.A. van den Heuvel, and J.H. Barrett; Nuclear Instruments and Methods B50 (1990) 127 (Ref. 3, p. 127).

17. U. Wätjen, D. Schroyen, E. Bombelka, and P. Rietveld; Nuclear Instruments and Methods B50 (1990) 172 (Ref. 3, p. 172).

18. N. Coron, G. Dambier, G.J. Focker, P.G. Hansen, G. Jegondez, B. Jonson, J. Leblanc, J.P. Moalic, H.L. Ravn, H.H. Stroke, and O. Testard; Nature 314 (1985) 75.

19. H.H. Andersen; Nuclear Instruments and Methods B15 (1986) 722.

20. S. Woiwod, R.M. Mueller, B. Stritzker, and S.H. Moseley; Nuclear Instruments and Methods B50 (1990) 91 (Ref. 3, p 91).

21. W. Kutchera; Nuclear Instruments and Methods B50 (1990) 252 (Ref. 3, p. 252).

22. P.E. Damon et.al., Nature 337 (1989) 611.

23. H.E. Gove, A.E. Litherland, and D. Elmore (eds), Proc. 4th Intl. Conf. on Accelerator Mass Spectrometry (North–Holland, Amsterdam, 1987) (Nuclear Instruments and Methods Vol. B29, 1989).

24. S. Namba, N. Itoh, and M. Iwaki (eds): Ion Beam Modification of Materials (North–Holland, Amsterdam, 1989). (Nuclear Instruments and Methods, Vol. B39, 1989).

25. K.G. Stephens, K.J. Reeson, B.J. Sealy, R.M. Gwillam and P.L.F. Hemment; Nuclear Instruments and Methods B50 (1990) 368 (Ref. 3, p. 368).

26. G. Dearnaley; Nuclear Instruments and Methods B50 (1990) 358 (Ref. 3, p. 358).

27. F. Watt and G.W. Grime (eds): Principles and Applications of High–Energy Ion Microbeams (Adam Hilger, Bristol, 1987).

28. K. Traxel; Nuclear Instruments and Methods B50 (1990) 177 (Ref. 3, p. 177).

29. G.W. Grime and F. Watt; Nuclear Instruments and Methods B50 (1990) 197 (Ref. 3, p. 197)J. See also G.W. Grime and F. Watt (eds.)Nuclear Microprobe Technology and Applications. (North–Holland, Amsterdam, 1987). (Nuclear Instruments and Methods, Vol. B30, No. 3, 1987).

30. W. Bauer et.al.; Nuclear Instruments and Methods B50 (1990) 300 (Ref. 3, p. 300).

31. R.W. Thomae; Nuclear Instruments and Methods B50 (1990) 444 (Ref. 3, p. 444).