Accelerators in Industrial Applications

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1. Introduction

Accelerators find growing interest for industrial applications in various fields e.g. as tools in very specified production lines as well as in research and development laboratories for analytical purposes. Accelerators are known as reliable instruments in nuclear physics since more than fifty years /1,2,3/. This is an important fact for the industrial application.
With a time delay of several decades these accelerators emerge more and more from research laboratories and penetrate into industrial applications. The move towards industrial instruments profits from long successful developments which include the careful studies of beam optics, the developments in vacuum technology as well as in electrical engineering and in general from the fact that more professional equipments are available today. That development is resembled in fig. 1., the accelerator tree.

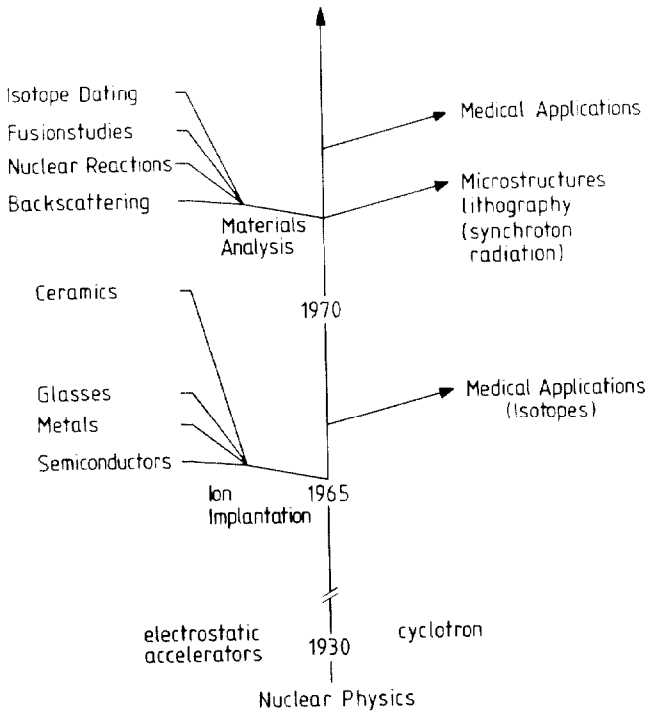

Fig. 1 Accelerator Tree

At the roots we find during the years 1930 - 1932 the electrostatic accelerators invented and developped by Robert van de Graaff /1/ and Raymond G. Herb /2/, the cascade generators for which Sir John Cockroft and Ernest T.S. Walton /3/ applied the voltage multiplication circuit due to Greinacher, as well as the cyclotrons developped by Ernest Lawrence /4/. All types of accelerators have now been used in industrial applications, however, the majority of presently applied machines for high energies are still electrostatic machines.
In the same sequence as they were developped, the accelerators entered the applications. Application resembles the fact that solid materials are bombarded by ions which in this way introduce well defined and well localized atoms in host matrices, a process which cannot be achieved by other methods, like alloying or diffusion. Semiconductor industry adopted as the first in the field the cascade generators with voltages up to 100, 200, or 400 kV as ion implanters in elemental silicon or compound semiconductors as GaAs or InP and many more. /5/ Ion implantation is presently a well established technical method not only for semiconductors but also for metals, ceramics and glasses. The vast amount of information about all nuclei in the periode table can be applied for the analysis of these elements in different host matrices. The detection limits for many elements favour the application of nuclear reactions for purposes of analysis. Even that presently particle energies in the range of a few tens of MeV are applied there is a strong move towards higher energies not only for the extended depth analysis but also for the MeV implantation for tayloring specific IC's. No direct industrial applications of high energy particles e.g. from synchrotrons are known but the mostly unwanted by-product of the electron synchrotron the synchrotron radiation is nowadays a heavily wanted radiation source for lithography and microtechnology. Special accelerators are under construction which serve the only purpose to produce the synchrotron radiation of different wave lengths. The application of unusual particles like muons and pions is still a field of basic research presently, there is no direct industrial application of such particles. However in medicine such particles have been applied to irradiate all kinds of living cells. This field is however, beyond the scope of that article.
Before we will discuss a few examples of applications we have to recollect the requirements of accelerators to be applied in industry. Many of these prerequisits are not necessary in research laboratories, because there a larger number of highly skilled people operate and maintain these machines whereas in industry more or less unskilled labour is available for that purpose. Thus the accelerators must have a very simple operation system which is safe to operators and customers. The handling should follow standard procedures and all instructions should be followed carefully. In many respects a computer controlled system will be the solution of that problem. The hart of each accelerator is the ion source to which the following criteria also apply:
The source must be as simple in operation as possible, it should have a design which allows long operation times because each down time is an important commercial factor. The ion source and its beam output must be reliable. This has been achieved in many installations by using separate ion source heads for each ion species, to avoid e.g.memory effects.
For ion implantation presently the following sources have been used:the Freeman source/6/,

the Sidenius source /7/, the Kaufman source/8/, the Baumann source /9/ and a variety of other designs.
For Tandem accelerators particular the machines from General Ionics and National Electrostatic Corporation the Middleton source /10/ has been successfully applied.

2. Application of accelerators

Accelerated ion beams have been already applied in many areas of industrial developments for which I will mention a few examples.

2.1 Ion implantation

Even that nuclear physicist have already used ion implantation as early as 1948 to produce solid targets of ^{2}H, ^{3}H and ^{3}He the majority of results emerged after 1958, after the basic patents have been filed. In close correspondence to the ion implantation the phenomen of particle interaction with solid materials had to be reinvestigated. Since particle penetration of solids produces lattice and structure damage, a thorough study of damage annealing was necessary for the scientific understanding of the processes involved. The best investigated material is silicon.
The industrial application of ion implantation started with the appearence of commercially available ion implanters in the beginning of the seventies. (Lintott 1970, Extrion 1971)
The requirements for instruments designed for use in industry are much more difficult to meet than in research laboratories, the above mentioned criteria also apply here.

2.2 High energy implantation

At the same time(1970) high energy implantation was studied in some suitably equipped laboratories.
Since that time the high energy implantation has become a very useful method for many applications /11/. As one example I want to mention the bombardment of silicon by MeV protons.
The proton irradiation of silicon lead to recombination centre distributions up to a well defined depth below the surface (3 MeV protons have a range of 100 µm). The maximum concentration appears near the proton penetration depth (buried recombination layer (fig. 2)).
Annealing at 350°C for stabilizing damage centres results in the formation of shallow hydrogen donors which affect the original doping profiles. This is advantageous for the irradiation of anode shorted Gate-turn-off thyristors resulting in a reduction of the on-state carrier density near the anode. By this means the tail current is reduced and the turn off loss is lowered by a factor of three as shown in fig. 3 /12/. The whole field of deep implantations covered presently are indicated in fig. 4 in which the fluence of ions and the desired energies are listed. Thus semiconductor industry is penetrating into the MeV implantation region.
Spezialized ion implantations aims at different fields of application. That can be seen for a few selected examples from fig. 5.where the ion beam current is plotted versus the ion energy.
The application of focussed ion beams (FIB) a very common technique in normal accelerator use, has found special interest in semiconductor industry for tailoring the very specific ICs and memories.
Several projects of high energy implanters are presently in the status of realization. Some use the RFQ structure for accelerating oxygen beams upto 10mA to a maximum energy of 3.5 MeV /13/.

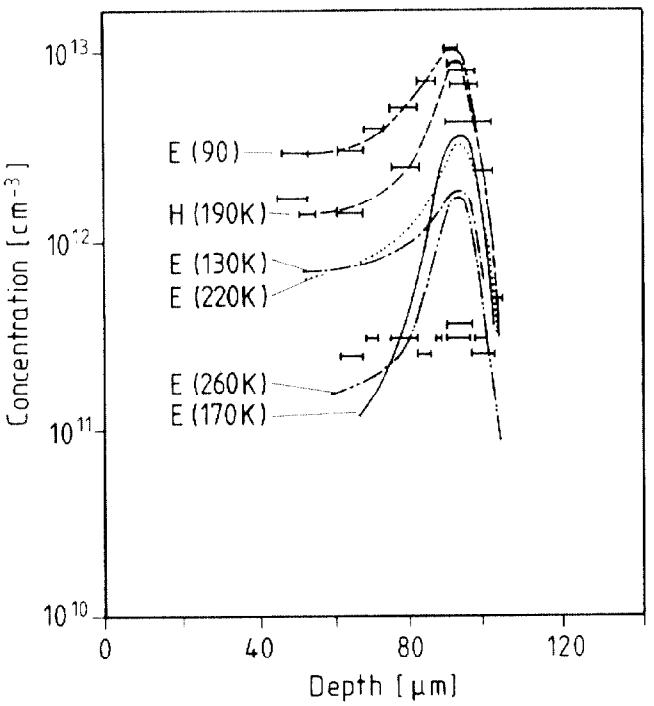

Fig. 2 Distribution of Defects in Si after Proton irradiation /12/

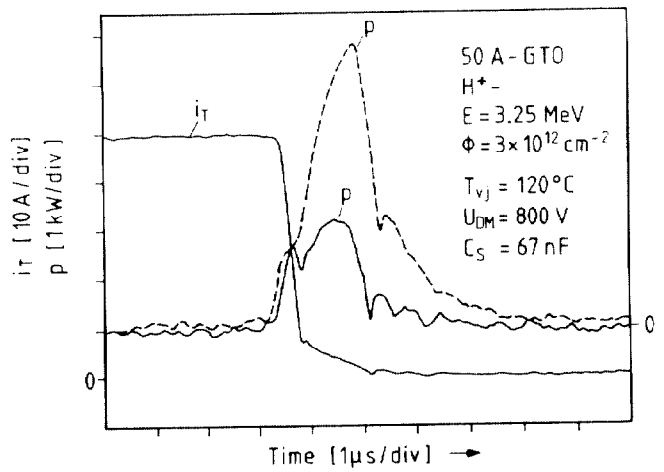

Fig. 3 Switching characteristics of a GTO Thyristor. Solid curve: H implanted, dashed curve: unimplanted /12/

2.3 Analysis Methods

2.3.1 Scattering analysis

The first materials analysis using Coulomb scattering was the testing of the composition of rocks on the moon /14/. Since then the Coulomb scattering has become a standard method for analysis of materials. Many laboratories are equipped with accelerators of about 2MV terminal voltage which is the usual voltage for the so called RBS (Rutherford Back Scattering) analysis.

In principle He^+ is used as projectile. The results of such analysis are shown in figs. 6,7 a,b.

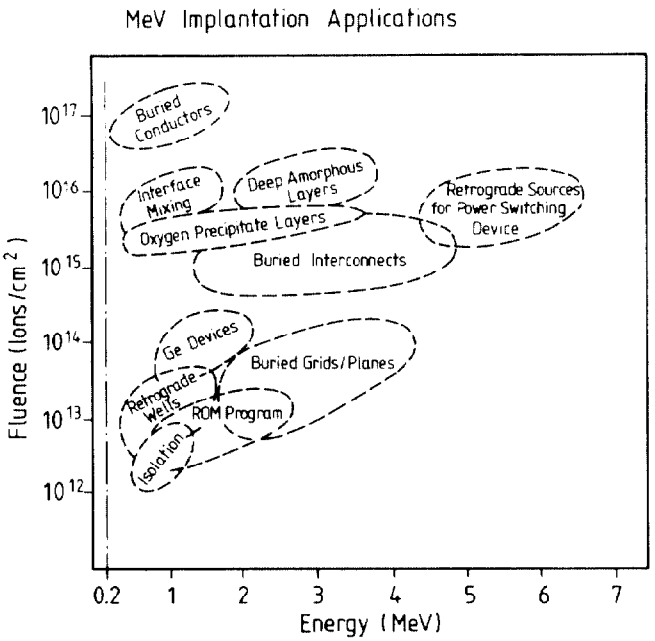

Fig. 4 Areas of high energy ion implantation/5/

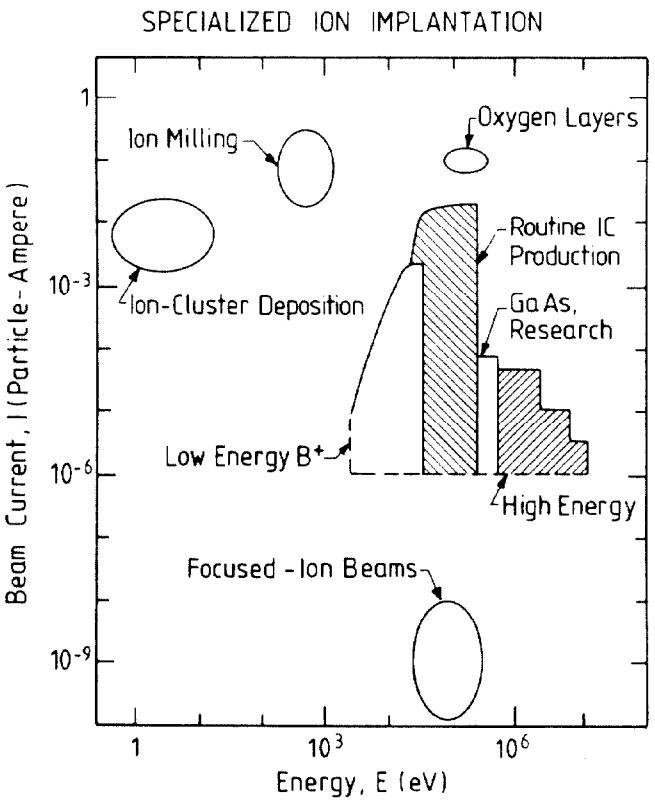

Fig. 5 Beam current - energy plot of specialized field of ion implantation /11/

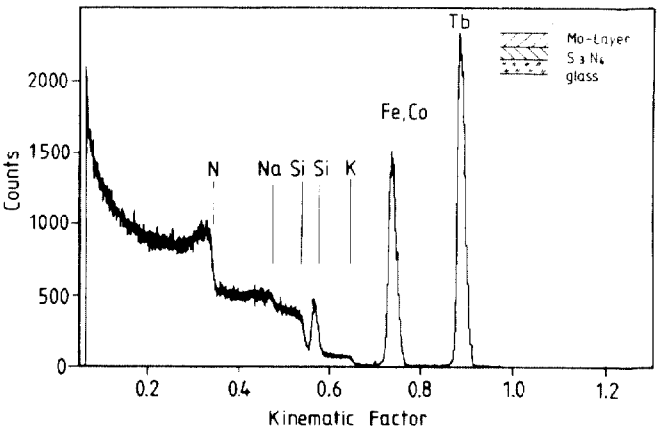

Fig. 6 RBS analysis of a magnetic optical layer

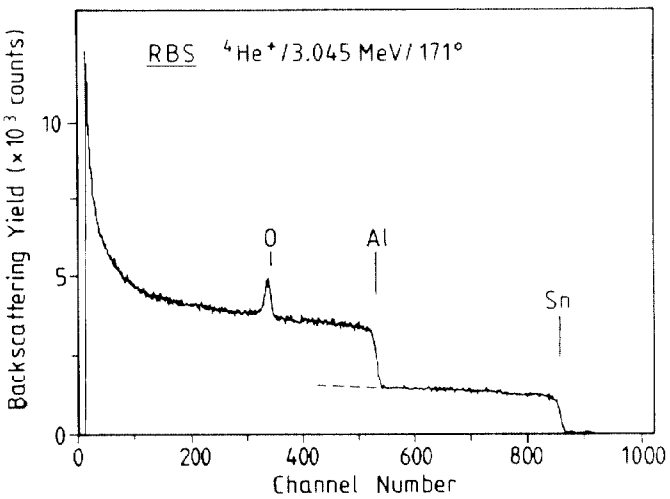

Fig. 7a RBS analysis of an AlSn-Alloy (Al:Sn = 84.5 : 15.5 wt%)

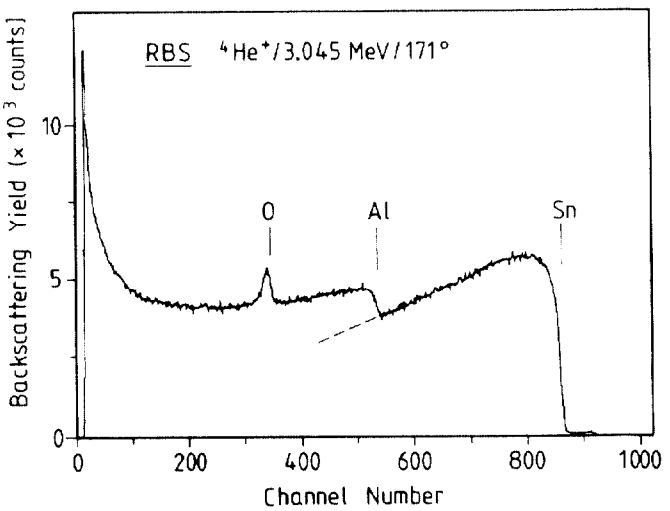

Fig. 7b RBS analysis of the same material as in Fig. 7a after application of heavy mechanical load.(at edge: Al:Sn = 48:52 wt%)

In fig. 6 the spectrum of scattered particles of a magnetooptical layer deposited on a sputtered Si_3N_4 layer on glass is shown. The magnetooptical amorphous layer is an alloy of cobalt, iron and terbium, all elements can clearly be seen in the spectrum, however, the masses of Co and Fe are that close that these two elements have not been resolved with the helium beam.
Furthermore the silicon from the insulating Si_3N_4 layer is clearly separated as a peak from the background silicon contained in the glass backing, which compounds Na,K and O produce a continuous spectrum.
Another example is shown in fig. 7 a,b. The composition of the surface of a splitbearing made from an AlSn alloy was analysed before and after an extended test period with heavy load. Originally the material contained 84.5 wt% Al and 15.5 wt % Sn homogenously distributed. After the treatment it was found that the tin content has moved to the surface indicated by the large Sn peak at the surface. This region now contains 48 wt % Al and 52 wt % Sn. The measurements were performed at an energy of 3.045 MeV which allows to profile oxygen. At an energy of 3.05 MeV a resonance in the cross section of the reaction $^{16}O\ (\alpha,\alpha)^{16}O$ exists which can be used not only to detect oxygen in its quantity, this resonance allows to profile the oxygen. Thus accelerators with higher voltages or equipped with an ion source which allows to extract reasonably intense beams of He^{++} will be of great advantage compared to the usual equipment. Furthermore with heavy ions as projectiles the resolution can be improved.

2.3.2 Nuclear reaction analysis (NRA)

During the last fifty years enormous material about nuclei has been collected, data on nuclear structure as well as data on reactions, particular cross sections are well known. These data can be used nowadays to detect and identify nuclei in different matrices. We can obtain information about element quantities by measuring decay properties of specific nuclei e.g. the stoichiometry. The detected abundances are in many cases comparable or better than achieved with other methods. Since the nuclear reaction analysis is an absolute method other laboratory methods can be calibrated. Nuclear methods do, however, not provide informations about chemical bonding or specific structures. The principle of NRA using the nuclear reaction A(a,b) B can be seen from the fig. 8.
Particles of species a penetrate into a layer which may contain an element A to some fraction. The nuclear reaction A(a,b)B transforms the nuclei a and A into b and B. The number of particles b emerging from the layer resembles the original distribution of element A. The yield curve can be analysed resulting in the number $N_A(x)$ of particles A which have been present in the sample in the depth x. The yield $Y(E_b)$ is given by

$$Y(E_b)\,dE_b = I \cdot N_A(x) \frac{d\sigma(E_a(x),\theta)}{d\Omega} \frac{\Delta\Omega\, d\,E_b}{dE/dx\ \cos\theta}$$

is the primary beam intensity of projectile a. The differential cross section $d\sigma/d\Omega$ as well as the energy loss dE/dx have to be known for a complete analysis. In fig. 9 an example is shown for an analysis of Carbon in GaAs using the reaction $^{12}C(d,p)^{13}C$. For the analysis a beam energy of 1.4 MeV has been used the analysed depth was about 6 µm /15/.
Although the NRA can be applied to analyse all elements and impurities it should be noted that in some cases interferences of nuclear reactions occur, resulting in the same final nucleus but originating from different elements. Then the application of different reactions allows in these cases a distinction of the reaction products.

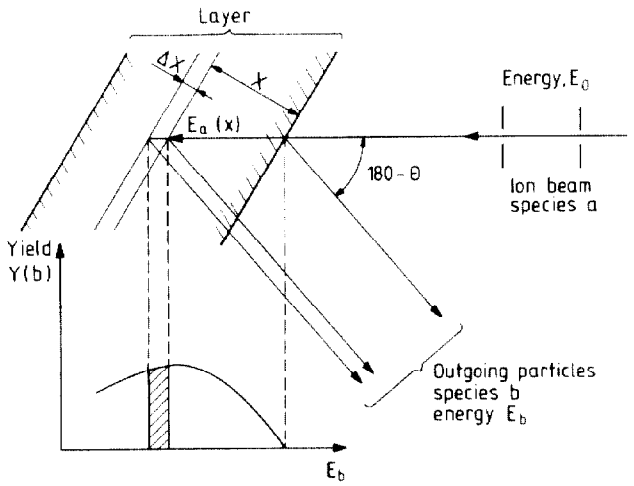

Fig. 8 Scheme of NRA

2.3.3 Charged Particle activation analysis (CPAA)

The production of artifical radioactive nuclei is one of the most efficient methods to detect impurities in highly purified materials. The analysis method consists of several steps. In the first step the sample is irradiated by an ion beam preferentially by ^3He or ^2H at an energy where the nuclear cross section has a sufficient magnitude (normally a few hundred mbarns). As an example the excitation function of the $^{12}C(^3He,\alpha)^{11}C$ is shown in fig. 10.

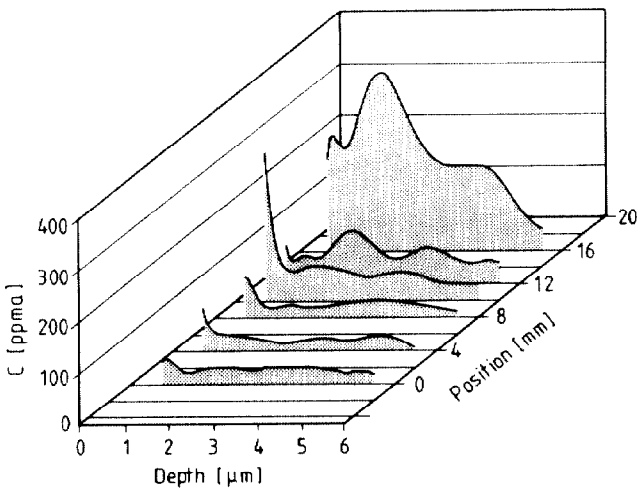

Fig. 9 Depth distribution of C in GaAs measured with the reaction $^{12}C\ (d,p)^{13}C$ at 1.4 MeV

^{11}C is a radioactive nucleus which decays with a half life of 20.4 min. After irradiation the surface of the sample has to be removed by etching because depositions on the sample from

the residual gas during the irradiation could also be activated and may thus influence the measurement. The usual etching proceedure takes about 1.5 min for which the decay curve has to be corrected. In the third step the decay of the activated nuclei is measured for at least five halflives /16/. The extrapolation of the count rate to the time at which the activation reaction stoped allows to determine the amount of impurity atoms. Fig. 11 shows for the above-mentioned nuclear reaction the cross section variation with penetration depth as well as the energy degradiation of the penetrating nucleus.

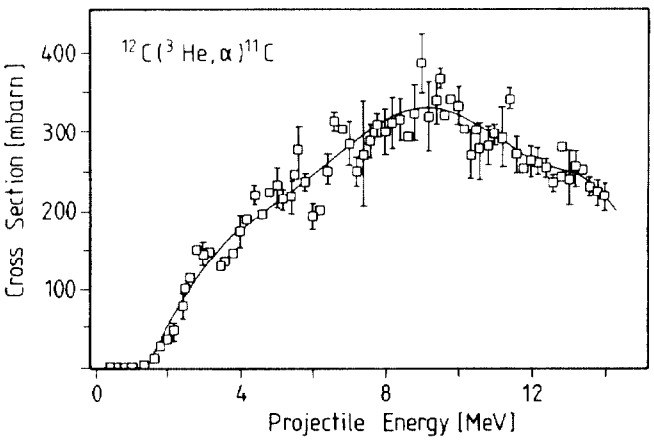

Fig. 10 Excitation function of the reaction $^{12}C\ (^3He, \alpha)\ ^{11}C$ for the analysis of C by CPAA

Both informations indicate at which energy the activation has to be performed and up to which depth the material can be analysed. Using this method it was possible for semiconductor material to calibrate IR measurements for oxygen and carbon on an absolute scale. The detection limits are for O: 10 ppba, C: 20 ppba, B: 50 ppba.

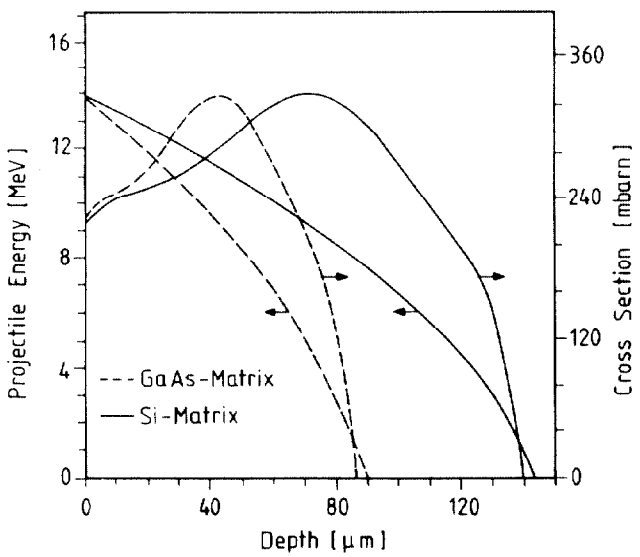

Fig. 11 Variation of projectile energy and cross section with depth for the $^{12}C(^3He, \alpha)^{11}C$ reaction

2.4 Irradiation of plastic material

A long tradition in the industrial application of accelerators has the electron beam irradiation of organic materials. Here a wide range of energies are applied from about 300 keV up to 3 MeV.
The principle effect in electron irradiation is the production of ions in the material treated by high velocity electrons which liberate orbital electrons. These electrons modify the chemical bonds between the atoms of the materials through free radicals interacting with the original structure.
By that treatment not only chemical structures but also physical properties can be changed. The molecular weight of bulk polymers can be tailored by polymerisation or depolarization. Also the creation of free radical sites provides grafting possibilities in the production of copolymers or converted materials. Polymers and elastomer crosslinking results in products which are more resistant to heat, stress and environmental decay. In the case of polyolefin film and tubing the electron beam treatment induces an elastic memory allowing usages such as shrink packaging material and heat shrinkable electric insulation.
Curing of coatings and adhesives on woods, metals and polymers eliminates the need for chemical catalysts or solvents and eliminates pollution and occupational safety problems associated with corrosive or toxic agents. The table 1 surveys the industrial applications of electron beam processing.
Presently for electron beam irradiation in the energy range 300 keV through 3 MeV insulating core transformers are beeing used. The energy of the electrons depends on the penetration depth of the different materials. /17/. Beam intensities up to 100 mA are used.
Since several years another irradiation of polymers became very important. This is the heavy ion irradiation of polycarbonat foils for the production of filter materials. This process is presently industrially applied but the irradiations still are carried out at research installations like GSI Darmstadt, Ganil Caen, Dubna near Moscow and Rossendorf near Dresden. For the production of holes in about 40 µm polycarbonats ions heavier than Kr with an energy of about 5 - 6 MeV/u are being used. /18/ (fig.12)

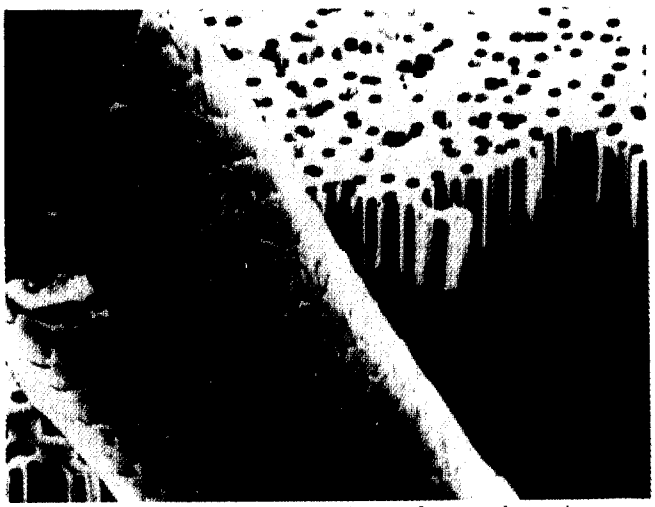

Fig. 12 Hole production in poly carbonate foils, human hair for comparison /15/.

The filters are needed in medicine as virus filters but also in semiconductor industry to clean the water for IC production. Even that there is a growing market no solely commercial accelerator is available for that purpose.

3. Industrial application of Synchrotron radiation

The energy loss of accelerated particles due to synchrotron radiation is an unwanted effect accompanying the research in elementary particle physics. The radiative power is proportional the ratio E^4/R (E, energy of the electrons, R, radius of the magnet ring). Thus high energy accelerators are built with very large radii. The radiation can however be applied in many areas of industry. Thus accelerators used for the application of x-radiation in a wide range of wavelength ($10^{-3} < \lambda < 10^{5}$ µm) are being built with much smaller radii as compact machines. Table 2 lists a few installations which devote a considerable part of the operation time to industrial applications.
The typical interactions of x-rays with matter involves absorption, reflection, refraction and scattering. Absorption of x-rays by core electrons occurs with a threshold energy but varies with the element. Therefore with a tunable source such as synchrotron radiation element specific studies can be made.
With respect to technical applications the analysis of microstructures of metal-polymer interfaces as well as metal semiconductor interfaces (V-Ge, Ni-Si, Ce-Si, Sm-GaAS) is presently being studied with synchrotron radiation. /19/
Particular for the production of very high density memories with microstructures smaller 0.5 µm the x-ray lithography is a very powerful tool.
Table 3 lists the present fields of application of synchrotron radiation.

4. Free Electron Laser

Another accelerator which gains interest for industrial applications is an electron accelerator which can be used as radiation source in the infrared region. That is the Free Electron Laser.
In existing installations electrons are accelerated to energies up to 3 MeV. At this potential the electron beam is magnetically deflected in a system of periodically arranged magnets, a wiggler system, where electrons emit synchrotron radiation. The physical process is equivalent to the scattering of electrons from a virtual Phononfield. The emitted Compton radiation can be fed back by means of an optical resonator and can cause in a reasonable dense photon field a stimulated emission of radiation. The elcctron beam is then decelerated to its original potential.
By that process only the small fraction of energy emitted as radiation is lost from the original power.
The radiation of that tunable light source can be used in processing materials and their surfaces. Primarily ceramics, glasses and compound materials will be used in much wider technical areas for e.g. at heavy duty parts than presently known. Laser welding with presently used lasers is not possible with these materials because of the limited penetration of the radiation. The uniform penetration into considerable depth can be achieved if the absorption behaviour of the materials are matched by proper wave length of the radiation. Thus the tunable FEL will be of great importance in the technical developments of the future.

5. Accelerators in industry

As above mentioned the application of accelerators in industry have to meet many requirements which normally do not restrict the use of these machines in research installations. Some of them are the overall reliability, the easy handling particular for non accelerator experts, the friendly maintenance, easy access to maintenance crews in cases of failures because each hour of non operation increases the investments costs.
A large variety of conventional ion implanters are already installed but the installations of accelerators with higher energies is still in the beginning.
A few of the presently available accelerators are listed in table 4 from which all machines with dominant application in medicine are omitted.
Still today many research instituts formerly dedicated to nuclear physics basic research offer now their installations to participate at the development in this new dimension of future technology.

Acknowledgements

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Table 1

Electron Irradiation

Industries	Processes	Products
Chemical Petrochemical	Crosslinking Depolymerization Grafting Polymerization	Polyethylene Polypropylene Copolymers Lubricants
Electrical	Crosslinking Heat-Shrink-Memory Semiconductor-Modification	Building Instrument Telephonwires Power cables Insulting tapes, Shielded cable splices, Zener Diodes, IC's, SCR's
Coatings Adhesives	Curing Grafting Polymerization	Adhesive Tapes Coated paper products, Wood/Plastic composites, Veneered panels Thermal Barriers
Plastics Polymers	Crosslinking Foaming Heat Shrink-Memory	Food shrink Wrap Plastic Tubing & Pipes, Molded Packaging forms
Rubber	Vulcanization Green Strength Graded Cure	Tire Components Battery Separators, Roofing Membrane

Table 3

Application of Synchrotron Radiation

	Semicond. industries	chemical	mechanical optical
EXAFS NEXAFS optical properties	X	X	X
Structure analysis	X	(X)	X
anomalous scattering	X		X
Photo emission	X	X	X
Trace element analysis	(X)	X	X
radiation damage	X	X	X
Lithography	X	X	X

Table 2

Synchrotron Radiation Sources (Selection)

		E(GeV)	R(m)	I(mA)	E_c eV	λ_c nm
3 Bessy I	Berlin	0.8	1.78	500	630	1.94
5 Bessy II	Berlin	1.5	3.82	100	1960	0.632
8 ESRF	Grenoble	5	3.56	500	12400	0.1
2 NSLS VUV	Brookhaven	0.75	1.9	1000	400	3.09
7 NSLS X-Ray	"	2.5	8.17	500	4200	0.295
1 ACO	Orsay	0.55	1.11	100	333	3.723
6 SRS	Daresbury	2.0	5.55	370	3200	0.387
4 Super ACO	Orsay	0.8	1.82	370	670	1.85

Table 4

High Energy Accelerators

Comp.	Acc.	Min Energy kV	max Energy MV	max current	Ion Source
HVEC	Electrostatic Acc.	100 200	1 2	He^+ 150μA	Microwave S Hot Cathode Penning Cold Cathode Penning
NEC	Pelletron Tandem		3 1.7	B^{++} 9μA P 5.5μA	SNICS
Eaton	Injection RF-Linac		1 2	500μA 100μA	Freeman S.
Ionex	Tandetron	100	1.7	B^{++} 10μA P 5μA	Duoplasm. Sputter S.
Physitec Disktron	charging by rotating discs 700 rpm.	60	1 (2)	30μA	PIG