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HIGH-ENERGY ION IMPLANTATION OF MATERIALS

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HIGH-ENERGY ION IMPLANTATION OF MATERIALS*

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ABSTRACT

High-energy ion implantation is an extremely flexible type of surface treatment technique, in that it offers the possibility of treating almost any type of target material or product with ions of almost any chemical species, or combinations of chemical species. In addition, ion implantations can be combined with variations in temperature during or after ion implantation. As a result, the possibility of approaching a wide variety of surface-related materials science problems exists with ion implantation. This paper will outline factors pertinent to application of high-energy ion implantation to surface engineering problems. These factors include fundamental advantages and limitations, economic considerations, present and future equipment, and aspects of materials science.

I. INTRODUCTION

This paper will emphasize the technique of simple, direct high-energy ion bombardment of materials for improvement or tailoring of near-surface properties. The energy range of interest is from about 25 keV to about 400 keV. Thus, the technique is to be contrasted with lower energy ion processing techniques, such as ion plating, chemical vapor deposition (CVD), or ion nitriding. The related, but more complex, technique of high-energy ion beam assisted deposition will be treated in a separate paper [1].

Development of high-energy ion implantation can partly be credited to the early nuclear industry, where ion production, acceleration, and mass separation were expanded into a sizable technology for isotopes separation. From the materials science standpoint, ionization of the atoms *per se* usually plays little to no role in the practical outcome, in comparison with, hypothetically, bombarding with fast neutral atoms of the same energy. Ionization facilitates acceleration, mass separation, and dosimetry for the bombarding ions.

Ion implantation currently finds its widest use in the solid state electronics industry, where the technique is used for introduction of dopants in carefully controlled quantities into elements of integrated circuits. Over 1000 ion implanters are in use for this

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purpose in the economically advanced nations. In part because of this success, research is now directed toward constructive modification of practically every surface related property in all classes of materials by use of high-energy ion bombardment. Goals include construction of insulating layers on (or buried in) conductors and semiconductors, construction of conducting layers on (or buried in) insulators, modification of virtually all possible surface optical properties, improvements in corrosion, catalysis or other electrochemical properties, improvements in wear and brittle failure, and fabrication of thin single-crystal films of artificial diamond, for example. Moreover, there are already a few other commercial successes for ion implantation, besides solid state electronics. These are mostly in the areas of biomedical materials, aerospace and defense materials, and certain production tooling.

In what follows, factors pertaining to use of direct ion implantation for surface engineering of materials will be identified and discussed. Examples of materials science results, applications, and possible applications will be given.

II. FUNDAMENTAL ASPECTS

As far as particle-solid interactions are concerned, there are four issues that are likely to come into play when any experiment or process design is considered. Fortunately, the applicable physics is now rather advanced, and results can be predicted with fair to good accuracy with quick, easy-to-use computer codes. The most widely used is TRIM [2], which is available for PCs free of charge.

A. Range-Energy

When energetic atoms penetrate into a solid, much of the energy loss is by elastic collisions with target atoms of the solid. As a result, atoms in a beam, incident at a given energy, are statistically scattered laterally and longitudinally as they slow down. The resulting depth distribution over which the implanted atoms come to rest is typically somewhat gaussian in form, but the distribution may also be skewed, depending on beam and target parameters. Figure 1 shows a typical ion implantation distribution for ions incident at a single energy in comparison with a TRIM calculation.

B. Radiation Damage

Due to the atomic collisions involved in the slowing process, many target atoms (typically about 1000) are displaced from their normal lattice sites in the target material.

This large energy deposition in the product is a unique aspect of high-energy ion implantation as a materials processing technique. The process is called radiation damage because target atoms are displaced. In fact, the results are as often beneficial as they are deleterious. The damage process can result in homogenization, refinement of microstructures, improved adhesion of ion treated layers, and amorphization. Numbers of displaced atoms are also calculable by TRIM. Ultimately, most of the vacancies and interstitials recombine to produce considerable healing.

C. Sputtering

Sputtering is another aspect of radiation damage in which knocked-on atoms near the surface are ejected from the surface. Sputtering yields (Y) are typically 0.2 to 10 target atoms per incident ion, depending on beam/target parameters. Thus, there is often no net addition of material to a target due to ion implantation, and many times there will be a net loss. One effect of sputtering is to limit the concentration of dopant that can be introduced by ion implantation. Because of erosion, the free surface is a moving interface, which moves into previously implanted volume. The resulting maximum concentration of dopant at saturation at the surface is about $1/Y$. Other aspects of sputtering include angular dependence of sputtering from each element of topography on the surface, angular dependence for shaped products in ion beams, and dependence on crystallite orientation. Distinctive surface textures can result from combinations of these factors (Fig. 2).

D. Heat

The high energy of the process eventually appears as by-product heat deposited directly in the target. One of the frequently claimed advantages of ion implantation is that it is a low-temperature process. The claim is true in that heat is not needed to achieve penetration. By-product heat must be managed, however. This is usually achievable by some combination of cooling and rate control for the implantation. Ion implantations can be performed over a range of temperatures from cryogenic to quite high values, depending on product requirements from the materials science standpoint.

III. GENERAL ARGUMENTS

A. High Energy, Chemical Flexibility, and Metastable States

Ultimately, the more impactful contributions of ion implantation may result from the fact that, in principle, the high energy of the process means that almost any chemical

species can be injected into almost any target—plastic, metallic, ceramic, or semiconducting—regardless of ordinary chemical reactivity. This means that a large variety of presently unknown metastable states, with potentially beneficial properties, could be created by ion implantation. Radiation damage also causes or aids in producing metastabilities, e.g., amorphization of many materials. Moreover, known chemical reactions can be employed in new and creative ways by use of ion implantation. Buried, insulating layers in oxide formers such as Si and Al are an example (ion implantation of oxygen). Reactive ion etching or polishing (ion implantation of F or Cl) is another. Together with temperature variation during and after processing, ion implantation allows a wider range of parameterization than is possible with most other types of surface treatments. A disadvantage is that considerable research and development is often required for development of a single product or process. Predicting engineering performance in advance of testing is difficult. Therefore, rapid economic advancement is not necessarily assured.

B. Thickness of Ion Treated Layers

The depths of ion treated layers in solid materials are generally less than $1\ \mu$ (Fig. 1). This is typically only about 10% of the depth of various coatings that are in competition for wear and corrosion protection. Thus, mechanical fragility is a possible problem, and perhaps to a greater extent, a perceived problem in marketing of ion implantation products and services. Actually, ion implanted layers can be more rugged than many suspect. For certain applications such as pure corrosion protection, without too much mechanical stress, ion implantation is more effective than many coatings because of extremely good lateral uniformity. In particular, this means absence of pores where corrosion events can nucleate. For cases where ion implantation has won markets in improved production tooling, tolerance has often been the key factor, together with difficulty in hardening the tool by competitive methods without loss of tolerance. Clearly ion implantation will nearly always be one of the last steps in manufacture of any product to which it is applied.

C. Cost

High cost is a major disadvantage of ion implantation if treatment of large areas is contemplated. Consider an ion dose of $3 \times 10^{17}/\text{cm}^2$, which is typical of what might be needed for corrosion protection or wear improvement of a metal product. The lowest cost that could be projected for processing materials to that dose in the U.S. is perhaps about $\$400/\text{m}^2$, with single modules of equipment of the type described below. This estimate

already takes into account some possible efficiencies of scale. Further improvement in costs may result from future equipment developments (see below), and very large scaling could presumably reduce costs a great deal. At present, ion implantation costs can be born by products such as nuclear fuel clad, hip joints, or other specialty products of high value. Even some industrial tools can bear such costs, but many products cannot. For large areas, costs per unit area will be approximately linear with dose. One avenue to cost reduction might be more optimal designs from the materials science standpoint, which might result in important dose reductions.

D. Environmental Factors

Ion implantation is regarded as one of the most, if not the most, environmentally acceptable surface treatment. One reason is that the process achieves excellent economy in use of feed material because of very effective application. For example, for the dose of $3 \times 10^{17}/\text{cm}^2$ mentioned above (a rather high dose) about 1 lb of Cr would be required to treat 1 acre of surface, or about 4 lb of the precious metal Ir would be required for the same number of Ir atoms as for 1 lb of Cr. Process discharges are correspondingly small and generally benign.

E. Other Factors

It is nearly impossible for an ion treated layer to spall off of a surface. This feature is of possible importance for performance, environmental, and safety reasons. Very precise dosimetry is possible, as for semiconductor doping, for example. Often there is no change in appearance of a surface due to ion implantation. This has been both an advantage and a disadvantage, depending on application.

IV. EQUIPMENT

A. Present Equipment

There are currently five types of commercial ion implantation equipment available. Concepts, intended purposes, advantages, and disadvantages will be presented. Four of the implanters are ion beam devices, but one is a plasma device that involves different concepts.

1. Magnetically Analyzed Plus Post Acceleration

This type of ion implanter, having emerged as the industry standard for solid state electronics, is by far the most widely used at present. It, therefore, provides a logical reference point for discussing competitive features. Figure 3 is a schematic layout of such an implanter. The ion source part of the implanter is usually a type of plasma source known as a Freeman source, but such a source may also be modified to allow for sputter ejection of ions into the plasma. By use of such a source in conjunction with suitable recipes, ions of most chemical species can be generated. After the ion source is an extraction/preacceleration stage, which brings the beam up to about 30 keV for magnetic analysis. The magnetic analysis stage reduces the beam to a single charge state of a single element (and generally a single isotope of that element), which is delivered to the mass analyzing slit. Thereafter, the beam is further accelerated in the post acceleration stage up to an accelerator potential of about 200 V. If the charge state is 2 instead of 1, the particle energy will be 400 keV instead of 200 keV. Typically there is a large sacrifice in beam intensity to achieve higher charge states than 1. After the accelerating column, beam optical devices allow delivery and rastering of beam to sizable targets in the vacuum end station, as desired.

This type of implanter provides several advantages but also provides the most expensive process of any of the implanters. The ion source, in conjunction with the magnetic analysis, provides the most chemical flexibility. The device provides the best overall quality control, including beam uniformity and dosimetry (on a flat area). Features also include a wider energy range than is usually found on competing implanters. Currents (about 10 mA) are lower than the others. In addition to use in the solid state electronics industry, this type of implanter has found general use. A disadvantage of all beam implanters is that shaped (not flat) surfaces must be manipulated in the beam to achieve uniform doses. A variety of fixturing devices are available to perform these operations in vacuum.

2. Unanalyzed Beam Gas Ion Implanters

Because of the costs associated with the analyzed beam process, a simplified design has arisen. This is the unanalysed, broad beam gas ion implanter (Figs. 4 and 5). This type of equipment is intended primarily for implanting metallurgical products with nitrogen ions for corrosion inhibition, wear inhibition, etc. Such an implanter can make use of more than one type of ion source and very large currents are possible. Capabilities of the sources themselves are not necessarily different from those of analyzed beam implanters. But since

ions of all constituents in the feed recipe are delivered to the product, chemical quality of the beam depends only on purity of the feed material. Thus, if a metal ion plasma were volatilized by use of a chlorination recipe, Cl ions would also be delivered to the target. For this reason, unanalysed beam implanters are regarded as most suitable for ions that can be generated from pure gaseous material such as N. Inert gases could also be used if there were a reason to, and hydrogen containing gases (methane, silane) could be used if the hydrogen were not a problem to the product. Capabilities of such implanters are as much as 100 mA at 100 kV. Without magnetic analysis such an implanter delivers both multiple ionization states (e.g., N^+ and N^{++}) and singly ionized molecular states (e.g., N^+ and N_2^+). Given that the accelerator potential is fixed, either effect amounts to particle energy dispersion, and therefore range dispersion, for delivered N atoms. The molecular effect is the larger of the two for ion sources used in these implanters. For metallurgical purposes, dispersion, instead of the more highly peaked implant distribution (Fig. 1), is often not a disadvantage. Accurate dosimetry may be compromised.

It can be argued that an ultimate advantage to this big beam type of technology, in comparison with plasmas that require magnetic confinement (see Pulsed Plasma Ion Implantation) is "scalability." This means that for sufficiently large single modular targets, or for a sufficiently large total area treatment rate, economies of scale are available for this technology, whereas for magnetically confined plasmas, even low energy ones, scaling up to areas above a certain optimum may become quite costly.

3. Analyzed Beam Gas Ion Implanters.

If silicon wafers (held at high temperatures) are bombarded with high energy O ions to very high doses, the O precipitates as an insulating layer of SiO_2 in the subsurface of the Si, and the single-crystal Si is retained at the surface on top of the insulating layer. This fact has given rise to advances in silicon-on-insulator technology and is known as the SIMOX process. For execution of the process, good control of range and dosimetry is needed. Eaton Corporation has developed a system for performance of the process. In concept the layout is similar to that of Fig. 3 in that magnetic analysis is provided. Single atoms of O at single values of energy can be delivered. The present system delivers 85 mA at 180 keV, but expansion in capability is said to be imminent. Presumably such a system could be adapted for use with other gases if a process were needed.

4. The MEVVA Technology

The MEVVA technology makes use of a vacuum arc ion source to generate high ion currents of metallic materials [4]. No gaseous plasmas are used in the source, and the only feed material needed is solid metal of the desired species. Thus, the source provides excellent vacuum quality for the target without use of extensive differential pumping. The source generates metal ions with a range of ionization states (but no molecular states) and the beam is delivered unanalysed. Therefore, pertinent remarks given above apply. The principle advantage of the system is economy in ion implantation of metallic species. The system is complementary in capability to the unanalysed gas ion implantation system described above. The beam is simply a cone diverging from the source, also. The source is in fact a rapidly pulsed source. At present, time-averaged capability is about 50 mA of current at 100 kV of accelerator potential.

5. The Pulsed Source Ion Implantation (PSII) Technology

The Pulsed Source Ion Implantation (PSII) technology [5] is the only currently existing high-energy system which is not a beam implanter. Thus, the ions are not in free flight when they impinge on the target. Instead, the product is a field terminal in the process. This technology is a derivative of fusion energy technology. Ions in a large plasma, generated by ECR microwave, or other means, are extracted directly to the target (product) by a pulsed, high-voltage supply. Arcing to the surface is prevented by the pulsing. This technology is most competitive with the unanalysed gas ion type of implanter. As with that technology, the PSII technology is intended primarily for use with gas ions, particularly N, but use with other gases is also possible. Hybridization or combination with other coatings techniques to achieve ion assisted deposition is also possible. The constitution of the ions delivered is about the same as for the unanalysed beam, in terms of molecular and ionization states. The most important advantage of the system is cost, and this advantage results in good part from the fact that the ions are incident at normal angles to essentially each surface element of the product. This means that manipulation of shaped products is not needed to achieve uniform treatment. Also, if sputtering presents a concentration limitation for beams, that concentration limit will be higher for normal incidence. Clearly there will be some loss of flexibility for treatment of insulators, since such products would at least have to have backing conductors of approximately the same shape.

B. Future Equipment

Ion beam processing equipment for the 21st century is being developed most intensively in Japan. A good fraction of the effort is under the auspices of a major joint government-industry initiative, and the corresponding agency is known as the Advanced Material-Processing and Machining Technology Research Association (AMMTRA). In addition to ion beam technologies, laser and other advanced materials processing technologies are being developed. The government contribution is said to be over \$100 M to the ion beam technologies, and in addition to equipment development, materials science research is also being supported. Competing industries, which are not a part of AMMTRA, are quite active also.

Table 1 summarizes the programs of AMMTRA in the area of ion beams [6]. Figure 6 is an illustration of the sheet ion system being developed by ULVAC. Such a system will be capable of processing very large areas.

Table 1. Summary of AMMTRA R&D Projects [6].

<u>Subject</u>	<u>Main Issue of Development</u>	<u>Target Specifications</u>	
		<u>Mid (FY 1990)</u>	<u>Fin (FY 1993)</u>
Development of high-current metal ion beam system [Nissin Electric Co., Ltd.]	1) high-current metal ion source and ion transport 2) ion beam technologies for surface modification	metal ion 100 keV (Al ⁺)	Al, Si ⁺ 100 eV–100 keV 100 mA (100 keV) modification area ≥100 cm ² current density 1 mA/cm ²
Integrated, high-current ion beam system [ULVAC Japan Ltd.]	1) high-energy, high-current ion beam system 2) low-energy ion beam system 3) in situ beam diagnostics	sheet ion beam 100 keV, 250 mA low-energy ion beam ≤100 eV, 1 mA	sheet ion beam 100 keV, 2A low-energy ion beam ≤100 eV, 5 mA

<u>Subject</u>	<u>Main Issue of Development</u>	<u>Target Specifications</u>	
		<u>Mid (FY 1990)</u>	<u>Fin (FY 1993)</u>
Ionized multiple beams technology with high deposition rate [Mitsubishi Electric Corp.]	1) cluster source with high deposition rate 2) uniform ion current density on wide substrate 3) excited gas source with high flux 4) compact designing of ICB source and gas source	200 mm diam. 0.3 $\mu\text{m}/\text{min}$	Al, Bi, Sr, Ca, Cu ion beams 200 mm diam. 0.1 $\mu\text{m}/\text{min}$
High-current focused gas-phase ion beam system [JEOL, Ltd.]	1) gas-phase ion source 2) He gas recondercer 3) focusing column for GPIS (gas phase ion source) 4) microlithography system	He ⁺ 2 $\mu\text{A}/\text{sr}$ ≤ 20 K $\leq 2.66 \times 10^{-7}$ Pa	He ⁺ ion beam beam diameter ≤ 10 nm 2 $\mu\text{A}/\text{Sr}$ 25 pA 100 keV
High-energy ion beam system [Hitachi Ltd.]	1) variable-frequency RFQ 2) microwave ion source for multiply charged ion beam 3) MeV ion implanter	≥ 1 MeV ≥ 0.5 mA (pulse)	0.5–4 MeV (variable) ≥ 1 mA
Surface improvement technology by ion implantation [Nippon Sheet Glass Co., Ltd.]	1) improvement of glass surface 2) evaluation of improved glass	improvement time = 1 h glass substrate □ 50 mm	improvement time ≤ 10 min glass substrate □ 300 mm
Modification of metal by ion implantation [Kobe Steel Ltd.]	1) improvement of corrosion resistance of Ti and carbon steel 2) improvement of wear resistance and surface hardness	evaluation of mini-sized sample	general corrosion rate ≤ 0.125 mm/yr Vicker's hardness ≥ 1000
Deposition of high-reflection X-ray mirror [Japan Aviation Electronics Industries, Ltd.]	1) design of optical systems 2) ion beam sputter deposition 3) ion beam deposition	reflection $\geq 20\%$ incident angle $\geq 5^\circ$, $\lambda = 1-30$ nm (25 mm) diam.	reflection $\geq 20\%$ incident angle $\geq 5^\circ$, $\lambda = 1-30$ nm (100 \times 100 mm ²)

V. MATERIALS SCIENCE

Each problem that arises is likely to need a specifically appropriate research and development approach and then a correspondingly specific process design. The following general remarks and illustrations are intended to provide ideas as to what might be possible.

A. Amorphization

Ion bombardment amorphizes certain materials whose chemical makeup lends a susceptibility towards amorphization. If this chemical predilection exists, amorphization usually occurs at a rather small dose. Therefore, amorphization will usually be quite inexpensive in any case in which it can be projected as having practical benefit. If the target does not have the suitable chemical character to start with, such character might be produced by high-dose ion bombardment. Then amorphization should soon occur. This latter pathway will generally be more expensive, however. The following chemical and other factors favor amorphization from the empirical point of view.

- Chemical bonding (in order)--covalent, ionic, metallic.
- Complex equilibrium structure for the chemical composition at the bombardment condition.
- Narrow composition range for equilibrium phase field (e.g., intermetallic "line" compounds).
- More elements.
- Two or more phases of differing crystal structure in chemical equilibrium at the bombardment temperature.
- Low melting point.
- Low-temperature bombardment.

Since bombardment temperature is a factor, a design choice as to whether to produce amorphization or not during ion implantation can sometimes be made. Amorphization can have varying effects. Ironically it can reduce brittle effects, provide isotropic deformation

modes, improve fracture strength, and reduce the elastic modulus for ceramic materials, but seems to make metallic materials more glassy.

B. Effects in Polymers

At low doses, ion bombardment produces increased cross linking, increased polymerization, and increased UV absorption [7]. At higher doses, hydrogen gas evolution, densification, and finally carbonization occur. Beam pyrolysis of photoresists painted onto metal surfaces can result in hard carbon coatings with excellent adhesion and properties [8].

C. Semiconductors

In addition to the doping and SIMOX process already mentioned, it is possible to produce a subsurface layer of cobalt silicide, which is fully metallic in conducting qualities [9]. Considerable research continues in compound semiconductors such as SiC, CdTe, and GaAs for which amorphization and epitaxial regrowth are special problems in comparison with Si. Ion implantation doping for solar cell production has been considered, and a non-mass analyzed system for ion implantation of P, using solid metal feed material was designed and evaluated [10]. The process is claimed to be economical and environmentally benign.

D. Metallic Materials

A variety of surface engineering approaches are possible, depending on problem details and economic factors. Simple nitrogen ion implantation often has very favorable effects on wear and fatigue of metals and alloys high in Cr, Ti, or Al. Nitrogen implantation usually does not result in improvement in friction. Treatments that result in carbonaceous or carbide coatings are possible. Figure 7 illustrates one successful case of salt-pitting corrosion protection for an aluminum alloy pillow block material for helicopters [11]. The application actually involved fretting corrosion. Fretting is considered to be a particularly favorable type of wear problem for approach by ion implantation because spalling is so difficult. The dopant that worked was Cr. Nitrogen ion implantation produces large increases in electrochemical salt pitting potential for aluminum, but corresponding increases in salt spray performance were not observed, as they were for Cr.

E. Ceramics [12]

Certain effects due to amorphization were identified above. Figure 8 is a Weibull analysis for engineering fracture stress of Al_2O_3 . Two types of ion implantation have been done. In the first, a high dose of Cr was used at room temperature. In the second, a low dose was used at temperatures where amorphization occurred. For many ceramics, the latter process would be much the more economical. For the amorphous case, the stress increases by a factor of nine for extrapolation to the cumulative failure level of 0.2%. In addition amorphization of ceramics might produce a variety of other benefits. Projected Hertzian stresses and stress concentrations arising in tribological situations might be reduced due to amorphization. Elastic and plastic compliance for adhesion to dissimilar materials might be improved.

For high-dose implantations, metallic dopants precipitate as metal particles in an Al_2O_3 matrix provided that the postimplantation anneal is done in vacuum. For annealing in oxidizing atmospheres, metallic dopants are incorporated as oxide alloys. Buried conducting thin-metallic layers, analogous to the planar buried conducting or insulating layers formed in silicon by ion implantation, have not been formed in sapphire.

Low-dose ion implantations in graphitic and glassy carbon produces dramatic improvements in wear [13].

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FIGURE CAPTIONS

- Fig. 1. Concentration versus depth for ion implanted 280 keV Zr in Ti-6 wt% Al-4 wt% V alloy. Experimental determination of the depth distribution by Rutherford backscattering spectrometry has been compared with that derived from a TRIM calculation.
- Fig. 2. "Cones and pyramids" type of sputter texture produced on a copper surface by use of a huge dose ($1.5 \times 10^{19}/\text{cm}^2$) of Ar ions at 40 keV [3]. Photograph courtesy of J. L. Whitton. The breadth of the area is about 3μ .
- Fig. 3. Schematic representation of a post acceleration type of ion implantation system, with magnetic mass separation of beam constituents. The target in the end station is intended to represent an array of orthopedic knee joints, which are being treated for improvement of wear performance.
- Fig. 4. Automotive crankshafts undergoing N-ion implantation. The beam diverges as a cone from the source and is unanalysed for mass, molecular or charge content. This facility is at AEA Industrial Technology: Harwell Laboratory, UK. Tecvac is a licensee of Harwell.
- Fig. 5. View of an ion implantation system intended primarily for use in ion implantation of large metallurgical products. This system is manufactured by Leybold and has capabilities not dissimilar from the system shown in Fig. 3.
- Fig. 6. Schematic representation of the "sheet ion beam" type of ion implanter. Development of this device is being done by ULVAC Japan, Ltd. as part the AMMTRA program.
- Fig. 7. Photograph showing coupons of 2014 Al, new, after various ion implantation treatments and salt fog testing (168 h), and as-tested with no ion implantation. Starting surfaces were all mechanically polished. Ion implanted areas were 2 cm in diameter, and the implanted samples were halved after testing. Cr ion implantation was very effective, reducing corrosion to almost nil. Oxide patches on unimplanted areas were up 30μ in thickness.
- Fig. 8. Weibull analysis for Al_2O_3 for fracture under four-point bending. As-polished, implanted-amorphous, and implanted-crystalline.

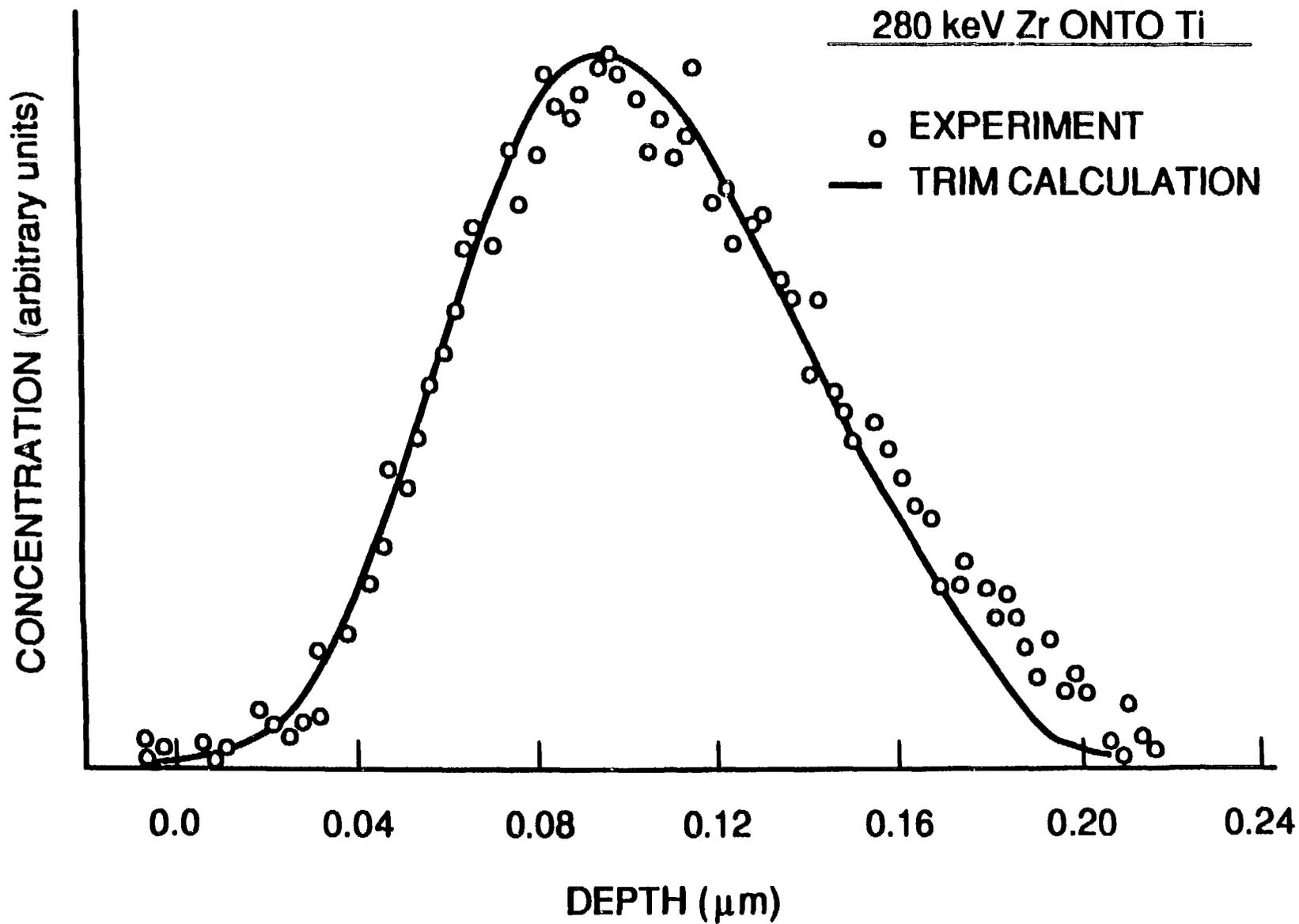
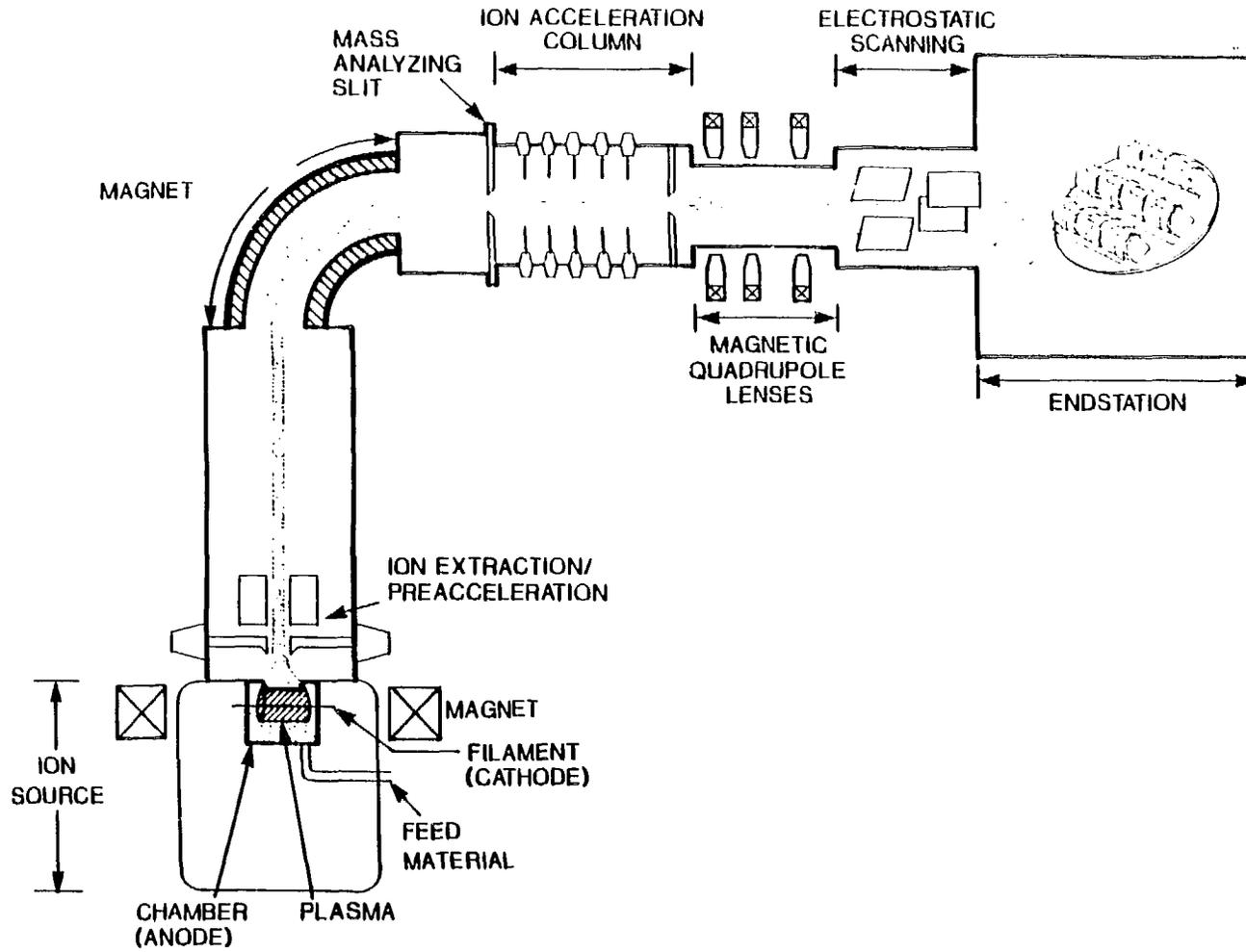


Fig. 1



Fig. 2

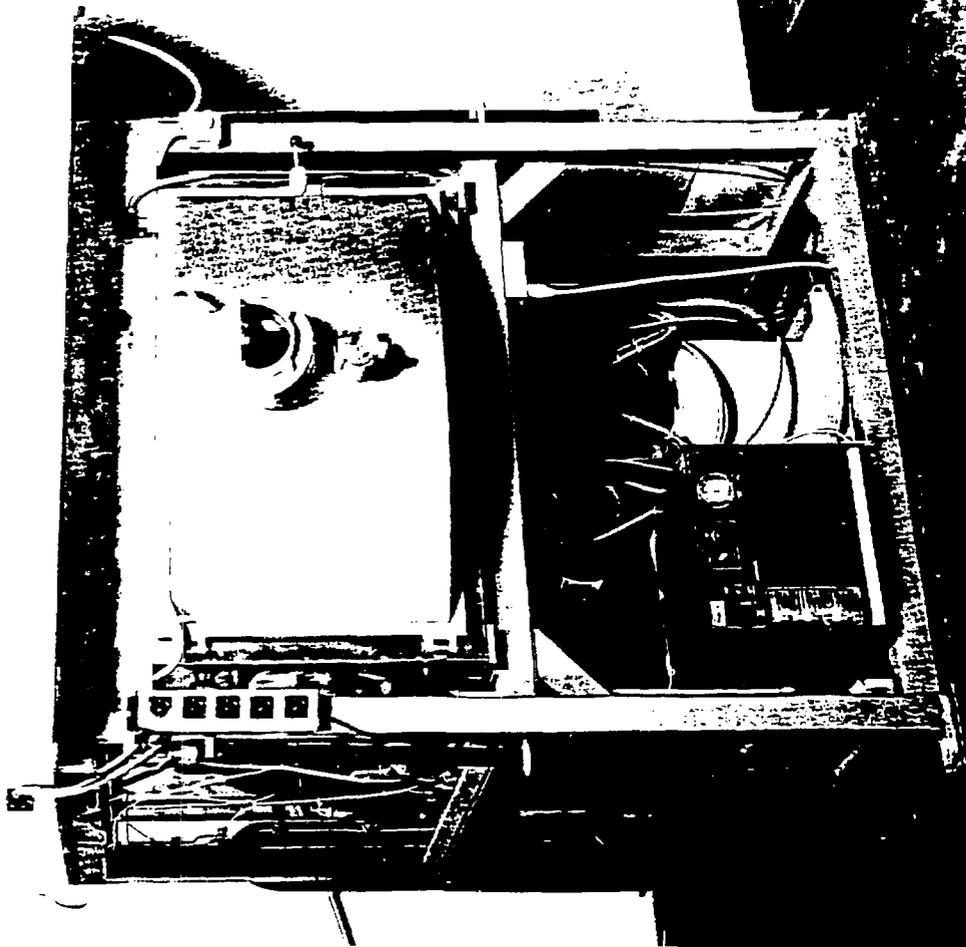
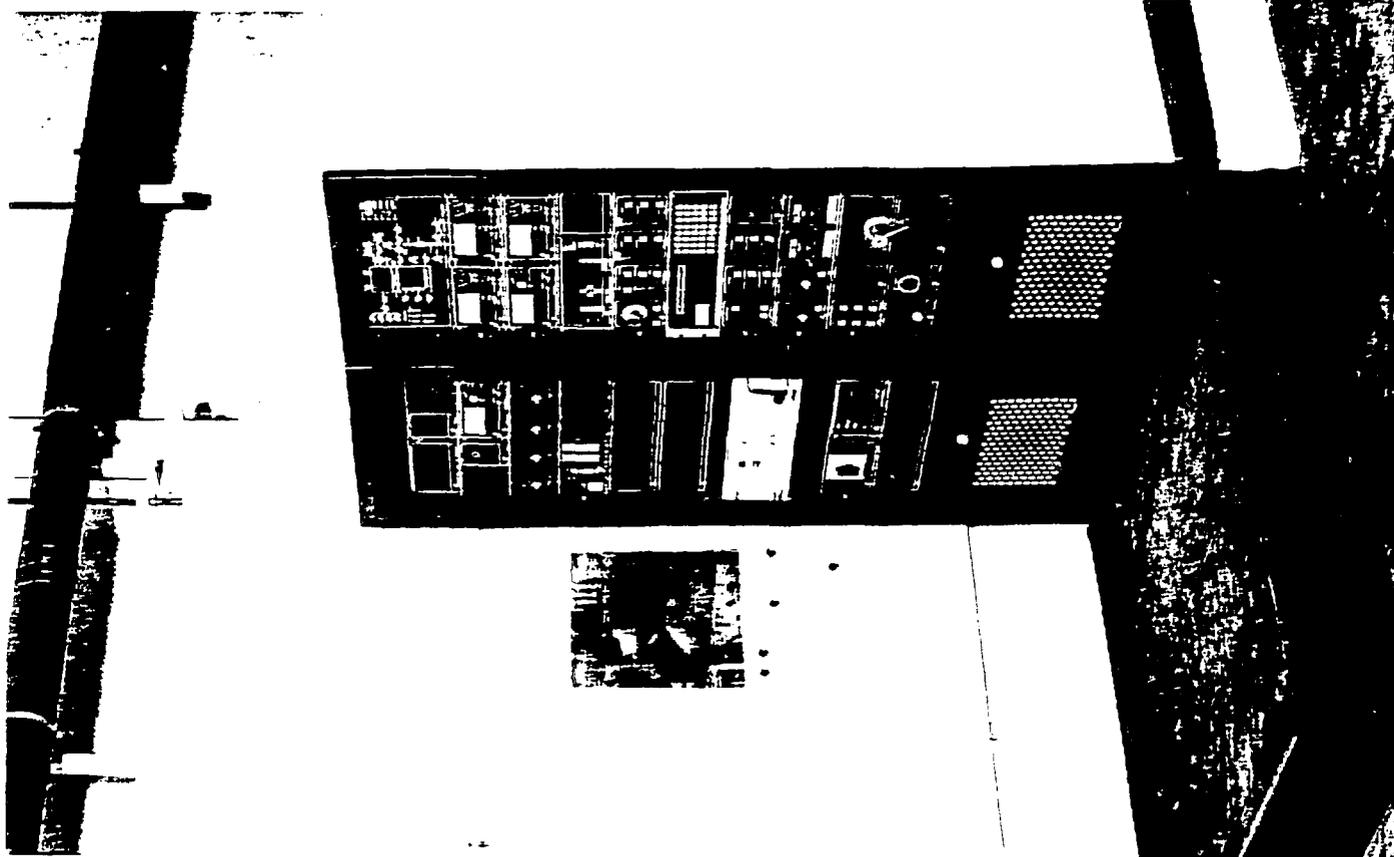


Drawing Courtesy of Spire Corp.

Fig. 3

**Production
Ion Implanters**





INTEGRATED, HIGH CURRENT ION BEAM TECHNOLOGY
TARGET: BEAM PROFILE OF 50 cm x 5 mm

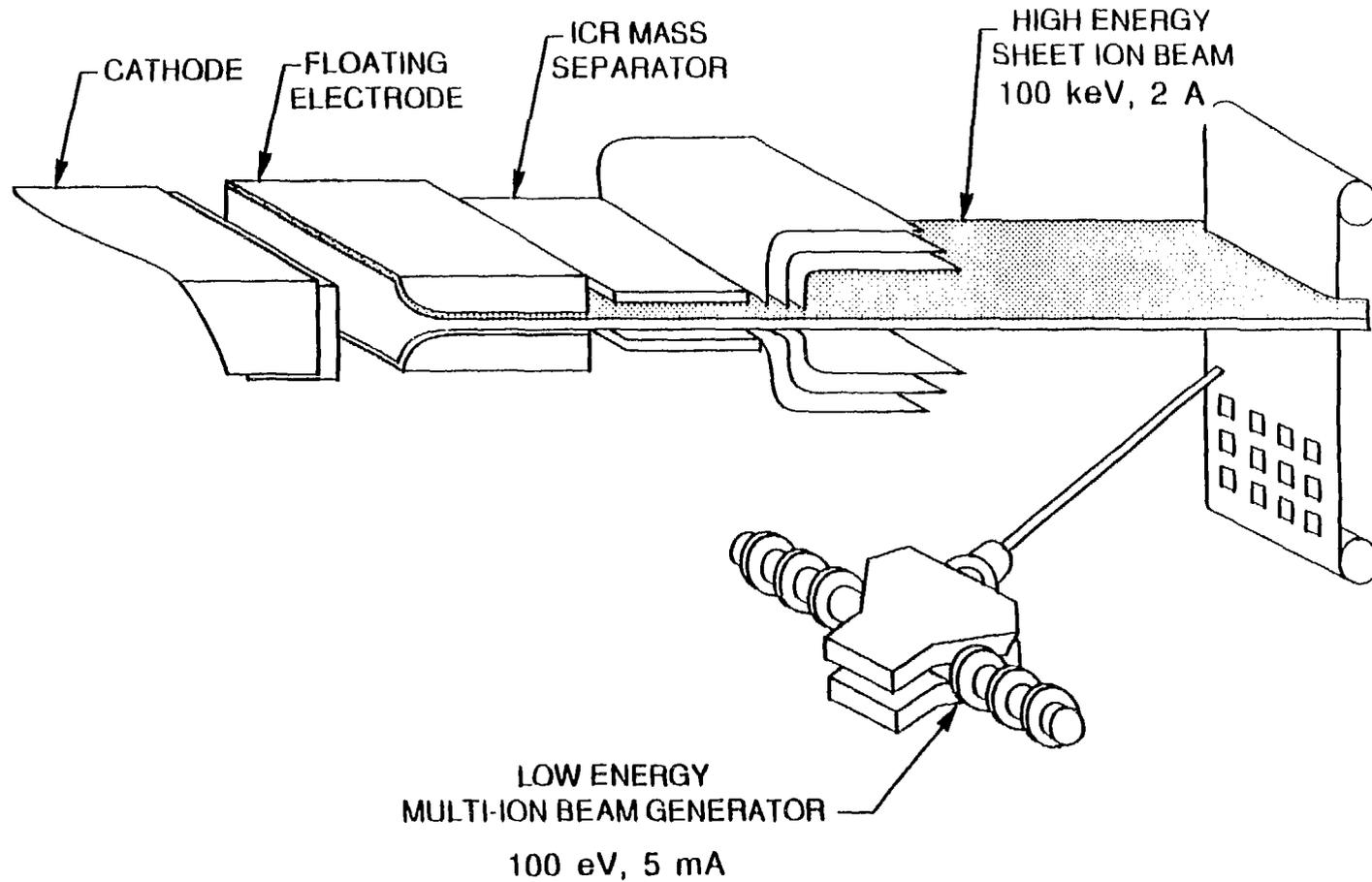


Fig 6

**2014 Al SAMPLES
MECHANICALLY POLISHED
ION IMPLANTED AS INDICATED
SALT FOG TESTED AS INDICATED**



NEW SAMPLE - UNIMPLANTED, UNTESTED



Cr-IMPLANTED, $3 \times 10^{17} / \text{cm}^2$ - 150 keV, TESTED



Ti-IMPLANTED, $3 \times 10^{17} / \text{cm}^2$ - 120 keV, TESTED



Si-IMPLANTED, $4 \times 10^{17} / \text{cm}^2$ - 60 keV, TESTED



Si-IMPLANTED, $2 \times 10^{17} / \text{cm}^2$ - 60 keV, TESTED



UNIMPLANTED, TESTED

Fig. 7

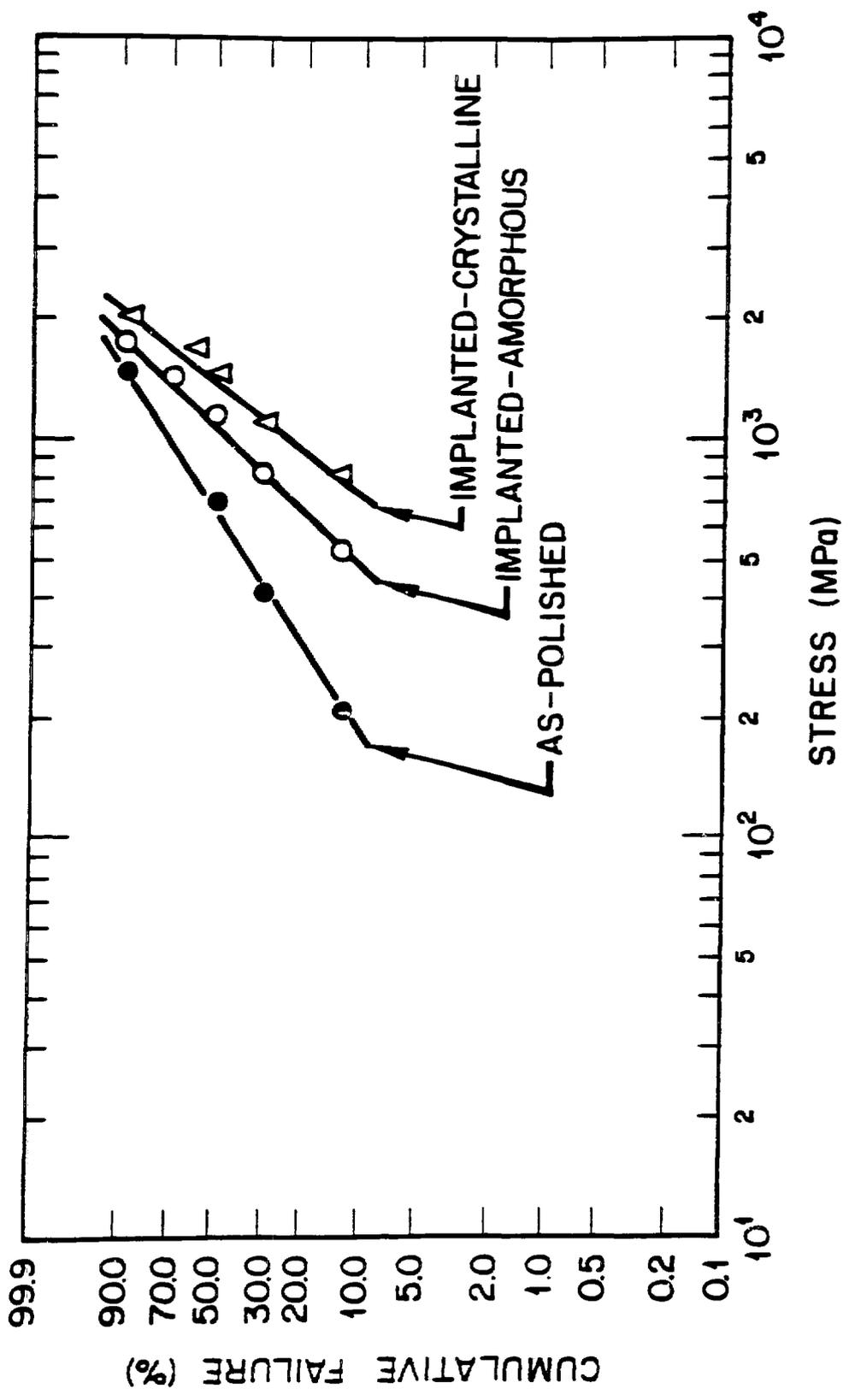


Fig. 8