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HIGH TECH METAL SURFACES USING ION IMPLANTATION

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1. INTRODUCTION

Ion implantation is a process in which an accelerated beam of ions of one material is injected into the surface of another material. In this way the atomic composition and lattice structure in the near-surface region of the target material is changed, and if the implant parameters are chosen judiciously, the properties of the new surface can be impressive. For the case when the target surface is metallic, the implanted material can be harder and smoother - it can have wear characteristics that are much superior to the unimplanted surface; resistance to fatigue can be greatly improved; resistance to corrosion can be increased by orders of magnitude; the electrical properties can be changed. It is a new field, and the potential for wide industrial application of the process is great.

Ion implantation has become common practice in the semiconductor industry over the last 15 years or so, and today the process is routine and central in semiconductor device fabrication. Silicon wafers are "doped" by implanting into them precise amounts of other elements such as phosphorous or boron; and the technology is crucial for the manufacture of new ultra-compact circuitry in which parts of the semiconducting device are buried below the surface. Semiconductor ion implantation is a well-established and accepted technology; metallurgical ion implantation is an emerging technology making the transition from research laboratory to industrial plant.
2. **THE PROCESS**

Ion implantation is carried out in a vacuum environment. Within the vacuum chamber, an ion source is used to create an intense beam of ions of the implantant species — the projectile ions. The ion beam is accelerated through a potential of perhaps 100 kilovolts or more, and transported to the target — the host material. The target is manipulated as might be necessary to expose the entire surface to the high energy beam. Some kind of target cooling might be necessary too, depending on the target mass and the beam power. Then the beam is run until the desired dose, or implantation concentration, is accumulated on the target. The process is illustrated simply in Figure 1.

The depth of penetration of the ions into the solid material is typically in the range 0.01 - 1 microns, and all of the new metallurgical properties are contained within this very thin surface layer. None-the-less, many important properties of metals — such as friction, wear resistance, and corrosion resistance — are surface properties, and the macroscopic behavior of the material can be profoundly altered by changes in the structure of the surface on the microscopic scale. Furthermore, it is observed that the advantageous effects of the implantation survive the removal by wear or corrosion of the original implanted layer, implying that some critical characteristics of the implantation propagate further into the surface as it wears or corrodes. This "depth enhancement" can be up to a factor of 100.

The implanted layer is not a coating. It is a part of the original material whose metallurgy has now been changed by the creation of a new alloy. Since the alloy is not a coating, it cannot flake off and it does not change the size of the object. A reason for the excitement that this new technology is creating is that in this way surface alloys can be formed that cannot be formed in any other way, and some of these alloys possess quite exotic properties.

A common implantant species is nitrogen. To a large extent this has evolved because it is relatively easy to create intense beams of nitrogen ions, and thus considerable research has been done on nitrogen ion implantation. Another ion species for which very encouraging results have been found is titanium. Nitrogen and titanium together show effective results, and this is generally thought to be due to the formation of hard TiN. Similar behavior is observed for titanium and carbon together, probably due to TiC formation.
As an example of some of the metallurgically beneficial effects of ion implantation, consider the commercial titanium-based alloy Ti-6Al-4V (titanium with 6% aluminum and 4% vanadium). This alloy is used for the manufacture of artificial hip joints and other bone replacements because of its excellent corrosion resistance and biological compatibility; approximately 100,000 total hip joints and 60,000 knees are surgically installed in the U.S. every year. Unfortunately the lifetime of such a joint in the body environment is under 15 years and revisions become necessary. However, nitrogen ion implantation of the alloy reduces wear by several orders of magnitude, well beyond the patient lifetime, with obvious advantages medically and economically. This alloy was originally developed for aerospace use, where fatigue resistance is critical. It has been shown\(^1\) that the fatigue limit, as measured by the number of cycles to failure in a test configuration, of the Ti-6Al-4V alloy can be increased by a factor of ten or more by carbon ion implantation. This is interpreted as being due to TiC and VC formation and consequent strengthening of the surface regions.

Many other examples can be found in the research literature: Nitrogen, carbon and argon implantation have been observed to reduce the wear rate of aluminum surfaces by a factor of about ten\(^2\). An improvement in the wear rate of beryllium, as measured by a lubricated pin-on-disk technique, has been measured after implantation with boron ions.\(^3\) The corrosion resistance of titanium has been improved by implantation with palladium - a reduction of three orders of magnitude in the rate at which titanium dissolves in boiling sulfuric acid was measured after palladium ion implantation.\(^4,5\) Similarly, molybdenum implantation into magnesium reduces pitting corrosion.

3. THE MEVVA ION SOURCE

Our own work at Lawrence Berkeley Laboratory (LBL) recently has led to some advances in metal ion implantation. The circumstances whereby this has occurred actually provide a nice case history of cross-discipline fertilization and technology transfer from basic research into applied technology. A major part of the fundamental research done at LBL is heavy ion nuclear physics, involving the study of the basic nuclear physics of heavy ions such as uranium, the heaviest element of all. This kind of research uses large particle accelerators - the Bevatron is the name given to LBL's heavy ion
synchrotron, a circular accelerator, and the SuperHILAC is a large Heavy Ion Linear Accelerator. In order to carry out ever more sophisticated experiments to probe the structure of the heaviest nuclei, LBL has an ongoing program to upgrade the performance of these accelerators, and one critical area for attention is the particle injector at the "input" end of the accelerator system. Thus is was that we initiated a program to develop a new kind of high current ion source that would produce vastly more current of uranium ions than had ever been possible in the past. This research led to the invention of the MEVVA ion source\(^{(6,7)}\), so called because the plasma from which the ions are extracted is made from a solid material in a vacuum environment by using a Metal Vapor Vacuum Arc discharge. This source has been successful in that it has produced beams of uranium ions up to 100 times more intense than was possible with other kinds of ion sources. The serendipitrous spin-off, however, is that the source can also make very intense beams of ions from all metals - not just uranium, thus removing what had been a bit of a stumbling block in the metallurgical ion implantation field - the difficulty of creating high current beams of metal ions. For this contribution to the technology, LBL was awarded a 1985 IR-100 award for the MEVVA ion source as "one of the 100 most significant new technical products of the year". A photograph of the MEVVA II ion source is shown in Figure 2.

We have done some preliminary ion implantation work using the MEVVA source. In one case we used a titanium carbide cathode within the source so as to produce a mixed beam of Ti and C ions; each of these ion species is created in several charge states, and the beam is composed of 6% Ti\(^+\), 45% Ti\(^{2+}\), 7% Ti\(^{3+}\), 33% C\(^+\) and 9% C\(^{2+}\). Each of these ion species and charge states is accelerated through the ion source extractor voltage, 25 kV for this experiment, and forms its own depth profile when implanted into the aluminum target with which we were experimenting. The resultant theoretical implanted ion concentration depth profile is shown in Figure 3. These calculations in fact agree well with the experimentally measured profiles.

4. **CONCLUSION**

Ion implantation into metals is a new technology. There is a vast amount of research and development to be done, both to learn those implants that produce the exotic surface properties, and to improve the implantation equipment available to users of the technology. It is very clear however, that
the improvements in surface hardness, wear resistance, and corrosion resistance, to name just a few of the more important surface characteristics, that can be obtained by this technique are very impressive. These improvements in quality guarantee that ion implantation for metallurgical use will grow into a major industrial technology within the next decade or so.
REFERENCES

Fig. 1 Schematic of the ion implantation process.
Fig. 2 The MEVVA II high current metal ion source. Overall length is about 18 inches.
Fig. 3 Calculated depth profiles, showing the relative concentrations of titanium and carbon atoms as a function of distance into the metal from the surface of the aluminum target material. Beam voltage 25 kilovolts.
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