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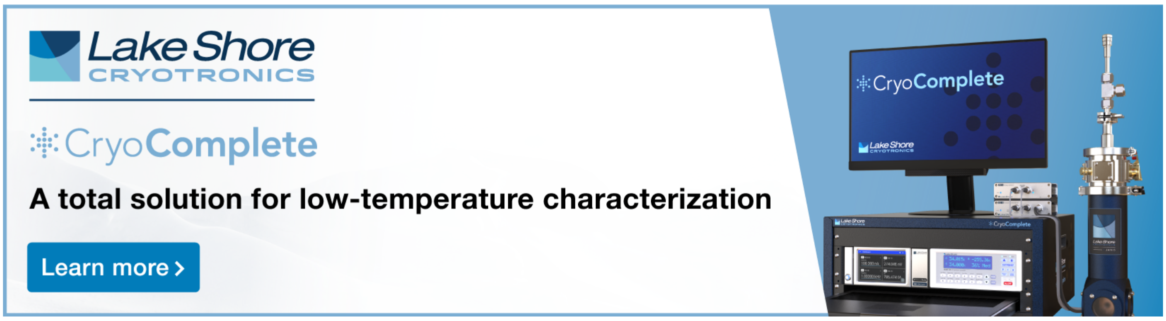

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Low cost ion implantation technique

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We describe an approach to ion implantation in which the plasma and its electronics are held at ground potential and the ion beam is formed and injected energetically into a space held at high negative potential. The technique allows considerable savings both economically and technologically, rendering feasible ion implantation applications that might otherwise not be possible for many researchers and laboratories. Here, we describe the device and the results of tests demonstrating Nb implantation at 90 keV ion energy and dose about $2 \times 10^{16}\,\mathrm{cm}^{-2}$. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4768699]

Ion implantation is a well-established technique for the surface modification of materials by the energetic injection of ion species into the near surface region, typically the uppermost few hundred Angstroms. Semiconductor fabrication is by far the most widely used application of the technology, and ion implantation systems for this purpose are by now very well developed; the technology is mature. However, quite apart from this widely known application, there is an active field of research worldwide in the surface modification of materials, specifically non-semiconductor materials, for other (non-semiconductor related) purposes, including, for example, improvement of the tribological and corrosion-resistance properties of metals and alloys, changing the near-surface properties of ceramics and polymers such as their surface electrical resistivity, fabrication of surfaces (metal, polymer, or other) that are biologically enhanced in various ways, tailoring of the composition of high temperature superconducting materials, synthesis of optoelectronic materials (typically by rare-earth doping), and much more. Research of this kind is actively ongoing and is reported in the literature and at a number of international conferences.[1] It is often the case that the ion implantation system used for this research is inherited from the semiconductor community, not unusually at considerable cost and with associated technical difficulties in initial set-up. Ion implanters designed and made for semiconductor application are often "overkill" in several different senses when the ion implantation need is for relatively small-scale research and often in small laboratories of limited means. There is thus a need for alternative approaches to ion implantation other than by the use of mainstream semiconductor-related implanters. We stress that this need lies not within the semiconductor community itself, which in general is well set up with high performance implantation technology, but within the non-semiconductor surface modification research community and in particular with investigators in small laboratories who would like access to this surface modification tool but are inhibited by the cost and set-up involved. Here, we describe an approach to ion implantation that can satisfy this need.

In a conventional ion implantation facility, an energetic ion beam is generated by an appropriate ion source, perhaps subjected to additional post-extraction acceleration but often not, and directed toward the target to be implanted. Energetic ion beams are conventionally produced by extracting ions (say, positive ions) from a plasma that is held at high (positive) potential, and the ion beam energy is determined by the potential drop through which the ions fall in the beam formation electrode system (called the "extractor" or sometimes the "accelerator") and by the ion charge state; $E_i = eQV_{ext}$, where E_i is the final ion energy, e is the electronic charge, Q is the ion charge state, and V_{ext} is the extractor voltage drop. In the simplest extractor geometry, just two electrodes ("extractor grids") are used. The first grid, nearest to the plasma ("plasma grid") is held at the same high positive potential as the plasma, and the second grid, nearest to the downstream region, is held at ground potential ("ground grid"). Additional intermediate electrodes are often used also, for example, to block the flow of back-streaming electrons ("suppressor grid") or to grade a very high overall extractor voltage drop ("gradient grids"). It is thus an inherent part of the approach that the ion source and its associated plasma-formation electrical system, often complex, be maintained at high positive potential, the extraction voltage. This necessity contributes vastly to the complication and expense involved in setting up an ion implantation facility.

An ion implantation system in which the plasma and its electrical system (the ion source) can be maintained at ground potential would provide technological and economic advantage. This can be done by maintaining the final grid and the space into which the beam is injected at high negative potential. In this case, the extractor voltage drop remains high and so also the ion energy, but with the overall potential profile falling from ground to high negative voltage rather than from high positive voltage to ground. Such an arrangement, in which the implantation target must be held at high voltage, may not always be feasible, but for much laboratory-scale ion implantation work, the savings in hardware simplicity and cost may well more than compensate for

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this inconvenience. Since the overall device potential profile is in a sense the inverse of that conventionally employed, we refer to the device as an "inverted ion implanter."

We describe a laboratory technique for carrying out ion implantation that by virtue of the modest hardware requirements provides access to this research field to investigators at small laboratories with limited means. The approach is simple and the electronics not sophisticated, and the facility can readily be assembled and implemented, while allowing ion implantation energy approaching 100 keV and dose in excess of 10^{16} ions/cm^2, as shown here.

In the work described here, we made use of a repetitively pulsed vacuum arc plasma gun to generate pulses of dense metal plasma. This kind of plasma source is used routinely at many laboratories, and the physics and principles involved have been well described in the literature.[2–4] We formed both Au and Nb plasmas using a small vacuum arc plasma gun incorporating either a gold cathode or a niobium cathode, subsequently injected into a bent-solenoid (sectional torus) magnetic filter to remove "macroparticles" (solid cathode debris). This plasma facility has been described previously.[5,6] The gun was driven by an LC (inductance-capacitance) pulse line of impedance 1 Ω and pulse duration 100 μs, providing a current of up to several hundred amperes at a repetition rate of up to about 5 pulses per second. The plasma stream exiting the bent-solenoid filter was directed toward the entrance of an appendage housing the negatively biased implantation chamber. Note that the filter serves the purpose of removing non-plasma components—particulates (cathode debris) and gaseous (un-ionized) material—from the plasma stream; there is no charge-state separation. In this way, the flux presented to the ion source extractor, and implanted, is purely in the plasma state, and the ion mix is the same as the ion mix formed by the plasma source.

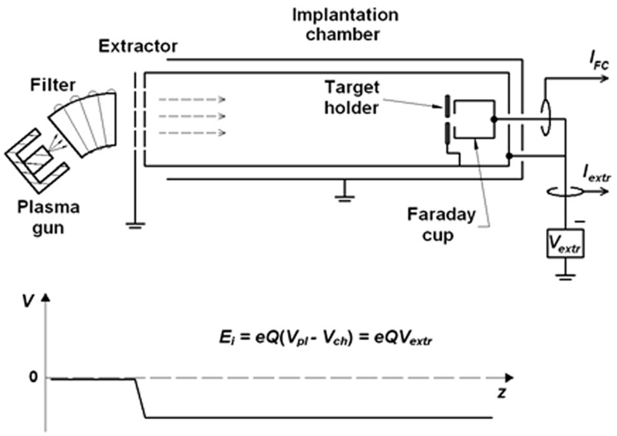

FIG. 1. Simplified schematic of the inverted ion implanter with filtered vacuum arc plasma gun, showing also the (on-axis) potential profile below ground.

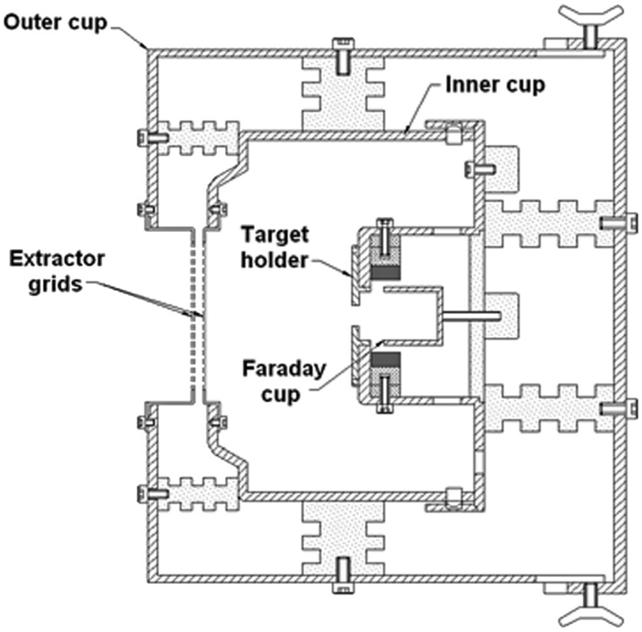

FIG. 2. The implanter device used here, showing the extractor grids, the outer (ground) chamber and inner (high negative potential) chamber, target holder, and Faraday cup. For scale: the diameter of the cylindrical aperture housing the extractor grid is 7.6 cm.

A simplified schematic of the setup is shown in Figure 1, and an outline of the implantation chamber in Figure 2. The plasma stream exiting the filter is formed into an energetic ion beam by the extractor grids that constitute the entrance aperture to the device. An outer cylindrical container is held at ground potential, in the front face of which is mounted the first grid. An inner cylindrical structure, well insulated from the outer grounded structure, is held at high negative voltage and the second extractor grid forms its entrance. The extractor is a multi-aperture configuration comprised of two grids, each having a large number (of order 100) of individual holes of diameter several mm (here 3 or 4 or 5) separated by 0.5 mm, and with separation between the two grids of 3 or 4 or 5 mm; good beam optics calls for appropriate extractor design, as discussed by many authors.[7–9] As the beam propagates downstream, the beamlets diverge and merge, smoothing out the initial beamlet structure. Calculations indicate that an axial distance of about 6 cm is more than adequate for memory of the beamlet structure to be lost, and here the implantation target is located at this distance from the extractor. A Faraday cup to monitor the implantation current density is located behind the target holder, with the holder geometry such that a known beam area is allowed to enter the cup. The Faraday cup is magnetically suppressed by means of a transverse magnetic field formed by a pair of samarium-cobalt magnets (with soft iron return flux path) at the entrance aperture to the cup, providing a barrier to the inward (into the cup) flow of cold beam electrons and to the outward flow of cold secondary electrons. This design of Faraday cup is known to provide reliable measurement of ion beam current. The Faraday cup current is monitored by a well-insulated current transformer.[10] The uniformity of the beam over the implantation area is primarily dependent upon the radial uniformity of the plasma stream that is presented to the extractor, which in turn depends largely on the geometry of the duct/filter and the spacing between the duct exit and the extractor. From prior studies of the plasma stream formed by the kind of vacuum arc plasma gun and magnetic filter as used here, we estimate the ion current density distribution at the implantation target to be uniform to about 10%–20% over the central 2 cm. That is, this configuration is appropriate for small samples, of dimension say 0.5–1.0 cm. Larger samples could be accommodated by an implanter specifically so designed.

For the experiments described here, the extractor voltage was in the range 5–35 kV. It is well established that the metal plasma formed in the vacuum arc discharge in general contains multiply ionized species.[11–13] For a gold plasma, the ion charge state distribution is close to $Au^{+}:Au^{2+}:Au^{3+} = 14:75:11$ (particle fraction percent) with mean charge state $Q = 2.0$, and for a niobium plasma $Nb^{+}:Nb^{2+}:Nb^{3+}:Nb^{4+}:Nb^{5+} = 1\%:24\%:51\%:22:2\%$ with mean charge state $Q = 3.0$. Thus the mean ion beam energy (keV) is twice the extraction voltage (kV) for gold and three times for niobium. References 11–13 provide data on the charge state distributions for vacuum arc produced metal plasmas for most of the metals of the Periodic Table, and these data can be used not only for the Au and Nb plasmas employed here but for any chosen cathode material, over a wide (and typically used) arc current range.

A typical oscillogram showing the arc current that drives the plasma gun, I_{arc}, and the Faraday cup current, I_{FC}, is shown in Figure 3. In this case, the extraction voltage was 30 kV (mean gold ion energy 60 keV) and the plasma gun arc current relatively low at just 70 A. The peak beam current into the Faraday cup was about 68 emA (electrical milliamperes). (Note that for multiply charged ions, the electrical current I_e is different from the particle current I_p: $I_p = I_e/Q$, where Q is the ion charge state.) For this measurement, the macroparticle filter was removed, and the Faraday cup entrance aperture was 2.1 cm in diameter; thus the ion beam current density was about 20 mA/cm^2. This corresponds to an implantation dose rate of 1×10^{13} cm^{-2} per second for a pulse repetition rate of 5 pps—quite high dose implantation can be carried out in modest time periods. (As a safety concern, we point out that as for all high voltage systems in vacuum with plasma, x-ray generation, here from backstreaming electrons, can become a serious personnel safety issue for voltages of about 20 kV or more. Appropriate x-ray shielding and monitoring are essential.)

For carrying out ion implantation, we positioned small samples on a rectangular piece of metal (the "holder") that was placed exactly half way across the circular entrance aperture to the Faraday cup. Thus, the targets were near, but not exactly at, beam center, and the Faraday cup remained still capable of monitoring ion beam current density during the actual implantation, and so the anticipated dose was calculable. To avoid the possibility of macroparticle contamination of the implanted sample, the bent-solenoid filter was inserted between the plasma gun and the implanter entrance aperture. Various test implantations were carried out at Au ion energy up to 60 keV and Nb up to 90 keV, corresponding to 30 kV extraction voltage, and with dose up to several $\times 10^{16}$ cm^{-2}. Rutherford backscattering spectrometry (RBS) was subsequently performed on some of the samples using a 3 MeV He^{++} ion beam at a scattering angle of 168°;[14] the backscattering data were analysed using the RUMP software package.[15] To improve the depth sensitivity, the samples were tilted at 55° with respect to the analysing ion beam. Figure 4 shows the RBS-measured implantation depth profile for the case of 90 keV Nb implantation into Si; the RBS-derived dose was $D_{RBS} = 1.83 \times 10^{16}$ cm^{-2}. This compares favourably with the dose expected from the measured Faraday cup current and number of pulses employed, $D_{FC} = 1.71 \times 10^{16}$ cm^{-2}, a difference of just 6%. From a number of different implants carried out, we can say that the implantation dose predicted from the measured Faraday cup current agrees with the RBS-determined dose usually to within a few tens of percent and always to well within a factor of two. The Faraday cup current might be monitored during the actual implantation if the target geometry so allows, or a prior calibration run might be done. The implantation profile expected from a TRIM (transport and range of ions in matter) calculation[16] is also shown for comparison; the known particle current fractions in the $Nb^{+}:Nb^{2+}:Nb^{3+}:Nb^{4+}:Nb^{5+}$ charge states were used and the TRIM curves for the different ion energies summed. The excellent agreement between the RBS-derived profile and the TRIM profile indicates that the ion implantation is as expected for this case.

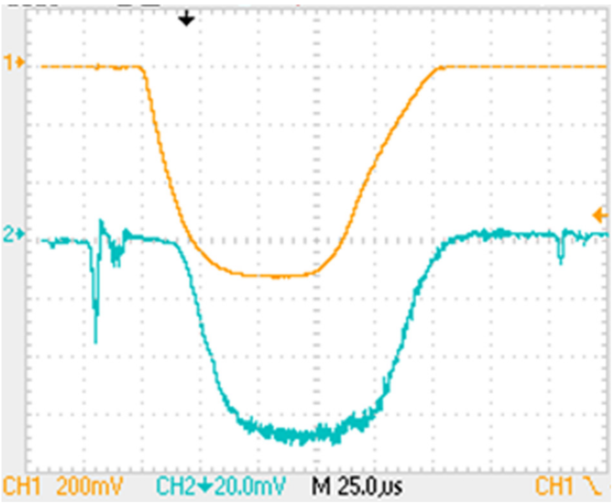

FIG. 3. Oscillogram of arc current (upper trace, 20 A/cm) and Faraday cup current (lower trace, 20 mA/cm); sweep speed 25 μs/cm. The oscilloscope was in average mode.

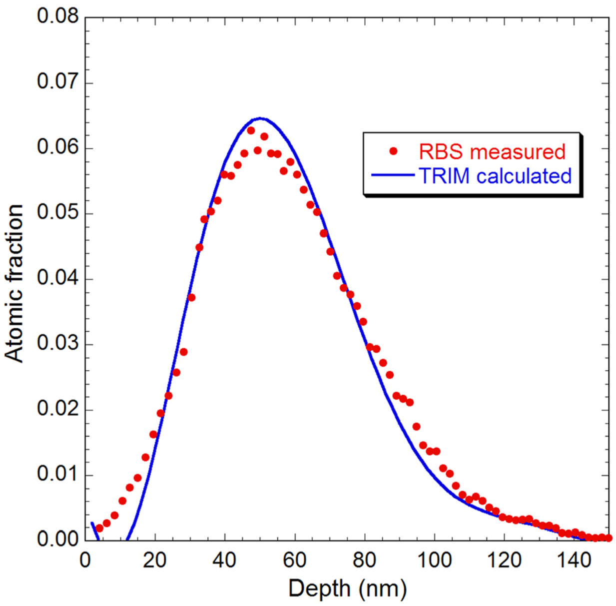

FIG. 4. RBS-measured depth profile for Nb implanted into Si at 90 keV, and the TRIM-calculated profile (obtained as the sum of the component profiles for the different Nb ion charge states).

The inverted implantation approach has some similarities to plasma source ion implantion,[17–21] commonly referred to also as plasma immersion ion implantation (piii or pi^3), an approach to carrying out ion implantation in which the substrate to be implanted is fully immersed in a plasma and repetitively pulse-biased to high negative voltage so as to accelerate ions from the surrounding high-voltage plasma sheath into the substrate surface. The pulsed nature of the high voltage substrate biasing is essential: during the pulse-on phase energetic ion bombardment takes place and depletes the plasma for some distance around the substrate, and during the pulse-off phase, the plasma is replenished. Plasma immersion has been extended to the case of a metal plasma, when the process involves both surface film deposition (during the pulse-off phase) and energetic ion bombardment (during the pulse-on phase); the acronym Mepiiid, for metal plasma immersion ion implantation and deposition, is widely used to refer to the process.[20–22] The inverted implantation approach embodies some characteristics of conventional "beam-line implantation" and some features of plasma immersion. As does beam-line implantation, inverted implantation derives its ion energy from ion acceleration at the ion source (extractor grids), as opposed to ion acceleration from the high voltage sheath surrounding a pulse-biased target in plasma immersion. This is important and has the consequences that the ion implantation (a) can be done with an insulating substrate and (b) can be extended to dc operation. Also, for the case of a metal plasma, the inverted implantation approach allows pure ion implantation, without the associated surface film deposition inherent to the Mepiiid approach. Additionally, the high voltage pulser required for plasma immersion is often a significant technological challenge, usually calling for high current and sub-microsecond risetime pulses, whereas the electronics required for inverted implantation is relatively simple and straightforward. There is, in fact, a conceptual spectrum of approaches to ion implantation, with beam-line lying at one end and plasma immersion at the other. Inverted implantation lies perhaps midway along that expanse.

The technique described here provides a simple and low-cost approach to ion implantation that could be appropriate and advantageous for certain laboratory applications. We used a repetitively pulsed vacuum arc plasma gun and formed a metal (Au or Nb) ion beam to demonstrate the method, but the approach can be applied to a wide variety of different kinds of plasmas, both metal and gaseous, and pulsed or dc. The (pulsed) ion beam current can be up to some tens of mA/cm^2 at ion energy approaching 100 keV, as here. The inverted ion implantation approach provides technological simplicity and economic savings to the challenge of setting up an energetic ion beam generation facility and may offer advantage, for example, for ion implantation research in a small laboratory on low budget.

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[1] See, for instance, the Proceedings of the Biennial International Conferences on the Surface Modification of Materials by Ion Beams (SMMIB) published in Surf. Coat. Technol. and the Ion Beam Modification of Materials (IBMM) published in Nucl. Instrum. Methods Phys. Res. B.

[2] *Handbook of Vacuum Arc Science & Technology*, edited by R. L. Boxman, D. M. Sanders, P. J. Martin (Noyes, Park Ridge, New Jersey, 1995).

[3] A. Anders, *Cathodic Arcs: From Fractal Spots to Energetic Condensation* (Springer, New York, 2008).

[4] I. G. Brown, "Cathodic arc deposition of films," Annu. Rev. Mater. Sci. **28**, 243 (1998).

[5] D. R. Martins, M. C. Salvadori, P. Verdonck, and I. G. Brown, Appl. Phys. Lett. **81**, 1969 (2002).

[6] M. C. Salvadori, L. L. Melo, A. R. Vaz, R. S. Wiederkehr, F. S. Teixeira, and M. Cattani, Surf. Coat. Technol. **200**, 2965 (2006).

[7] P. Spaedtke, "Computer simulation of extraction," in *The Physics and Technology of Ion Sources*, 2nd ed., edited by I. Brown (Wiley-VCH, Weinheim, 2004).

[8] R. Hollinger, "Ion extraction," in *The Physics and Technology of Ion Sources*, 2nd ed., edited by I. Brown (Wiley-VCH, Weinheim, 2004).

[9] T. S. Green, Rep. Prog. Phys. **37**, 1257 (1974).

[10] Pearson Electronics.

[11] I. G. Brown and X. Godechot, IEEE Trans. Plasma Sci. **19**, 713 (1991).

[12] E. Oks and I. Brown, "Vacuum arc ion sources," in *The Physics and Technology of Ion Sources*, 2nd ed., edited by I. Brown (Wiley-VCH, Weinheim, 2004).

[13] I. Brown and E. Oks, IEEE Trans. Plasma Sci. **33**, 1931 (2005).

[14] W. K. Chu, J. W. Mayer, M. A. Nicolet, T. M. Buck, G. Amsel, and F. Eisen, Thin Solid Films **17**, 1 (1973).

[15] L. R. Doolittle, Nucl. Instrum. Methods Phys. B **9**, 344 (1985).

[16] J. F. Ziegler, J. P. Biersack, and U. Littmark, *The Stopping and Range of Ions in Solids* (Pergamon, New York, 1985 (new edition in 1996)). The computer code is downloadable from the SRIM website.

[17] J. R. Conrad and T. Castagna, Bull. Am. Phys. Soc. **31**, 1479 (1986).

[18] M. A. Lieberman, J. Apl. Phys. **66**, 2926 (1989).

[19] J. R. Conrad, R. A. Dodd, F. J. Worzala, and X. Qui, Surf. Coat. Technol. **36**, 927 (1988).

[20] A. Anders, *Handbook of Plasma Ion Implantation and Deposition* (Wiley, New York, 2000).

[21] See the proceedings of the Biennial International Workshops on Plasma-Based Ion Implantation and Deposition, generally published in Surf. Coat. Technol.

[22] I. G. Brown, X. Godechot, and K. M. Yu, Appl. Phys. Lett. **58**, 1392 (1991).