

ION IMPLANTATION FOR SHALLOW DEVICE FABRICATION BY USE OF THE CATHODIC ARC ION SOURCE,

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The cathodic arc technology is the newest viable entry as a candidate technique for the problem of shallow junction doping for logic and memory circuits. The present paper compares results from the technology with those already better accepted in terms of ion-solids interactions considerations.

INTRODUCTION

Development of the boron cathodic arc ion source for high-value applications has been underway for some time (1,2,3,4). Possible applications include orthopedic coatings (5), depositions for neutron detectors (4), semiconductor doping, and others. Among these, shallow junction doping for logic and memory circuit production would be by far the most economically important application and also the most exacting. The present paper will concentrate on certain fundamental aspects of ion-solid interactions, pertinent to Si doping, with comparisons among the cathodic arc approach and the other presently-favored methods, namely PIII or "PLAD," and ClusterBoron™ or Clusterlon® (6) techniques. First a brief review, describing the technique, advantages and disadvantages and certain achievements and issues to date will be presented.

REVIEW

The key aspect of this program has been development of the boron cathodic arc ion source. Reference 7 is a good tutorial for the technology. In general a cathodic arc source differs from other ion sources in two very important ways. First, it requires absolutely no gas for operation, though it can use a gas for supplementary purposes if desired. Hence the other name *vacuum arc source*. Secondly, the emergent low energy beams (30 eV e.g.) or "ion plumes," are very robust in comparison with extracted beams from gas ion sources, with up to 30 A in instant current being possible (8). The present B ion source can operate at 2 A of generated plasma, although an average of about 1 A is anticipated, and a useful current of about 200 mA average is expected after the "filtering" process to be described. The standard cathodic arc source produces ions only of the solid cathode material, which is usually a metal. The boron cathodic arc ion source is part of an emerging technology of cathodic arcs operating with semiconductor (e.g. Si), semimetal (e.g. B) or conductive ceramic (e.g. B₄C) cathodes. The key feature of this technology is the use of cathode heating to render the cathodes conductive enough to draw the arc current, as well as to improve the resistance of the cathodes to thermal stress. Development has moved forward in small steps, driven by specialized government agency needs and funded by corresponding small business contracts. Now this technology is reaching maturity and is entering the realm of prototype scale-up for industrial applications. Reference 3 provides the most complete summary thus far of properties related to semiconductor manufacturing applications.

The most important disadvantage of the vacuum arc source is that much of the cathode comes off as "macroparticles," so called. Such particles are of about 10 μm in dimension. Eliminating these particles from the stream is mandatory for a successful application to doping. There are a

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large number of filter designs. An excellent filter has been developed for B (or C) as part of the present program. Figure 1 illustrates certain aspects of the filter, and also provides a visual picture, which gives good intuition as to the nature of the arc plume.

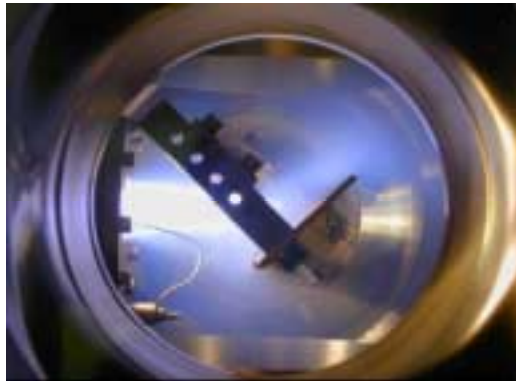


Figure 1. Passage of plasma through the filter. The unfiltered plume of about 2 A of boron enters at about 9 o'clock. The filtered plume of about 400 mA exits at about 2 o'clock. Then the filtered plume is re-channeled in the original direction by magnetic ducting. The baffle system is not shown.

The plume, of about 2 A of positive B ion intensity, enters the chamber from the ion source at about 9 o'clock. Clearly, from the degree of collimation of the beam at this intensity and energy, space charge compensation is excellent. The operation of the filter has been described previously (3) and will not be detailed. The filtering process consists of a magnetic deflection of the plume by use of plates carrying high currents. Bouncing particles are trapped by a surrounding baffle system. The entire geometry is designed to allow no particles in to a certain central aperture area for up to one million particles launched and for up to ten bounces of each particle. The design principles could be used to design a filter applicable to a larger area if desired.

The plasma consists of single atoms of singly charged B ions, at least by the time it reaches the target (see below). The preferred delivery mode is by target bias, as in plasma immersion, with the plume impinging on the target.

In addition to pure B, cathodes of several other materials have been successfully operated. These are:

- Boron carbide
- Pure C
- Semiconductor grade Si

There appears to be no reason why Ge could not be operated as well as Si. There are also plans for acceptable n-dopant cathodes. Thus, a concept for a processor would include a carousel type of cathode mount, providing for rapid and efficient changing from one function to another, together with the high current advantages of cathodic arc___ pre-amorphization with Ge or Si, C implantation for TED inhibition (9), and doping. No magnetic analysis would be required, and, of course no gas. Thus, such a system could be quite compact, safe and environmentally clean.

Including the particle issue, previous research has concentrated on the following areas. Some are on-going, seeking further improvement or new products, and some of which appear not to be a problem for eventual production worthiness.

- Particle filtering

- Cathode production, composition and lifetimes
- Impurities delivered assesment
- Anode atoms incorporated into target (none)
- Range-energy and doubly charged ions (none apparently)
- Firing reliability (for pulsing)

Uniform distribution and dosimetry for 30-cm wafers has not yet been studied.

RESULTS AND DISCUSSION

Results, analyses and comparisons are presented in Figures 2 through 4. The main point of this discussion will be to help establish the credibility of the arc results. That is because of the relative paucity of data from this technique as compared with ones that have been pursued for several years.

Figure 2 shows a comparison of junction depths (for $10^{18}/\text{cm}^3$ concentration) produced by several experiments, three of which (10,11,12), involving PLAD or plasma immersion (PIII), were published at the recent IIT-2008 Conference. Issues and comparisons for these data will be discussed with reference to several possible relevant factors, including:

- native oxide on the surface during implant
- channeling and pre-amorphization (PAI)
- energy contamination due to free B ions in cracking pattern
- factors affecting channeling other than PAI
- SIMS technique

A important point in the compilation is the point for Clusterlon® at 500 eV (13). The beamline point is from the same reference. Besides the points for cathodic arc, this Clusterion® point is the lowest point for the given energy in the compilation. Given that the Clusterlon® technique claims self amorphization and that the technique should also provide for minimal energy contamination, it seems reasonable to adopt this point as a tentative standard. Most of the other data range higher in junction depth for the given “nominal” energies. Ultimately, we are interested in the credibility of the arc data, and are looking for a reason why this technique might yield results that are somewhat lower than other target bias techniques. The arc data are in excellent agreement with Clusterlon®. It seems likely that the generally higher values for the immersion techniques are due to some combination of channeling and energy contamination.

In discussing the data, we will not make much of relatively minor differences, given that the data are not dose-normalized, there may be differences in SIMS sputter ion energies, etc. That statement would apply to the difference between the Varian and PULSION data, for example.

Perhaps the most obvious point is that all of the data tend to converge at low energies. In itself, that is not surprising. Possible contributing factors will be discussed. However, the data are not tending to extrapolate to zero depth at zero energy. Without another idea, the most likely explanation would seem to be that this latter point is due in good part to ion mixing during SIMS and represents a limit due to ion mixing. Does this result then suggest that one should subtract off approximately 4 nm from junction depth measurements by SIMS, in general?

In our view, the roles of possible energy contamination, amorphization, and oxide on the surface are somewhat intermingled among these various results.

Figure 3 shows “raw” SIMS data for the present cathodic arc technique, for which the derived junction depths have been plotted in Figure 2. The point being noted at present, however, is the small break in slope at about 10 angstroms, and the “peakiness” below that depth in relation to what would be the extrapolation of the (nominally) logarithmic slope from above that mark in

depth to below. We believe that this effect is due to the native surface oxide for our results and probably some of the others. In the absence of more detail than is presented in these concise papers, one cannot be certain.

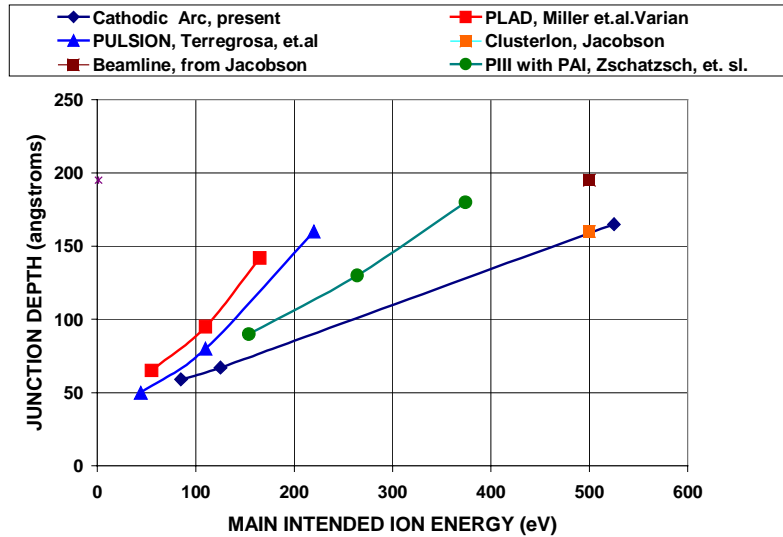


Figure 2. Comparison of junction depth (10¹⁸/cm³) results among several examples of doping techniques for B ions. The abscissa title is based on the idea that, for PSII or PLAD, the most important effective implant ion energy will be 0.22 X the bias voltage, because of the shared energy of the B constituent in the BF₂ ionized molecule. For Clusterlon® the value for the single B atom is an appropriate fraction of the B₁₈H₂₂ ionized molecule energy.

For the present data, the samples were etched by the usual 10 % HF treatment and introduced in to the vacuum as soon as possible for implantation, but there was no interlock for rapid introduction in to the vacuum and the mechanical mounting process was somewhat slow. Undoubtedly there was plenty of opportunity for oxidation, since it would readily occur even in the residual vacuum.

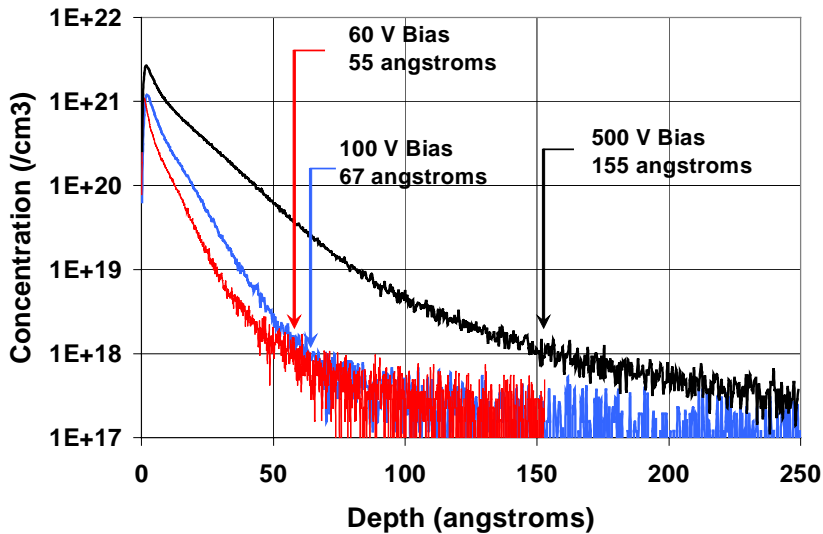


Figure 3. SIMS analyses of concentration versus depth for cathodic arc implanted B ions at the bias energies shown. Actual entrance energies may be somewhat greater than the biases because of the intrinsic energies of the arc plume (see text).

The probable role of the oxide is illustrated by the TRIM (14) results of Figure 4. First, the implanted boron concentration is somewhat higher in the oxide than in the pure Si substrate. This result is fairly typical for low-energies, as is the local minimum in the boundary region. Second, sputtering calculations for oxygen (generally used in SIMS) indicate that the sputtering yield for the oxide is about twice that of the pure Si. Thus if the sputtering yield of the oxide were assumed in the calibration to be the same as the average from the dimple, the resulting equivalent Si depth would be only half of actual, and the corresponding measured concentration would be twice as great as otherwise derived, even without the extra concentration of B in the oxide. Moreover, possibly the minimum may help to delineate the slope change, even with ion mixing. While these arguments do suggest a strong influence of the oxide layer in the near-surface structure of SIMS data, we have been unable to model the actual data in detail.

We cannot state the degree to which this effect plays a role across all of the results in Figure 2. However, Zschätzsch et.al (12) may have noted such a slope change at about 10 angstroms. Whether this is the transition to the “channeling tail” noted at $\sim 10^{20}/\text{cm}^3$ we do not know. This observation was made despite the fact that the material was pre-amorphized.

Thus, as far as channeling as a function of energy is concerned, two effects that tend to be offsetting could come in to play. Both are a result of the (fundamentally tautological) relationship between atomic collision cross sections and energy. There would be a tendency to scatter to higher angles during transport through the oxide, so that channeling would tend to decrease as energy decreases. Also, there is less transmission through the oxide at lower energies. On the other hand, the acceptance angle and channeling width for channeling increases with decreasing energy. We suspect that the first effect is the more important.

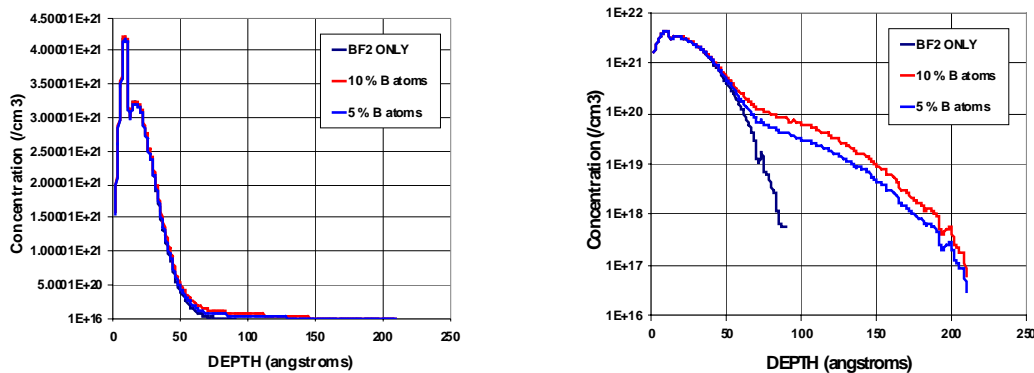


Figure 4. Linear (left) and log (right) plots of concentration versus depth for 220 keV incident energy of BF₂ and for a corresponding energy or 1 keV for free boron atomic ions added in possible proportions to cracking yields for BF₃ gas, and with the target bias at 1 keV. Also, the Si target is assumed to have a 10-angstrom oxide layer on the surface. Calculations by TRIM (14).

Again using TRIM, the exit angles for individual B ions transmitted through the oxide have been calculated. Using 10 degrees (much greater than an acceptance angle) as an arbitrary and crude criterion, it is found that only a .045 fraction of 60-eV incident ions transmitted through a 10-angstrom oxide would be within this angle and a 0.21 fraction would be within such an angle for an incoming energy of 500 eV. Thus, another reason for convergence of the data at low energies in Figure 2 could be a relative absence of channeling for all samples, amorphized or not. The total fraction transmitted for 500 eV is 0.93 and the fraction transmitted for 60 eV is 0.35.

It is clear, however, that channeling is important at higher energies. This conclusion is demonstrated most prominently by the data of Zschätzsch et.al [12] at a polarization of 1.7 keV (374 eV as plotted for the B component) for both crystalline and PAI. The result for crystalline material is not shown, because the graph was truncated. However, the junction depth could have been about 350 angstroms. Also, data from the same experiment with PAI have lower junction depths than do the other two immersion techniques, but not as low for the given energy as Clusterlon® and cathodic arc.

Even so, besides showing the possible effect of the oxygen layer, Figure 4 (right) demonstrates that energy contamination could also be playing a role. While we do not know the detailed cracking pattern for BF_3 in the plasma immersion chambers, ones for sources such as Freeman, Bernas and IHC sources are well known. Renau et. al. (15) show a pattern for a source tuned to maximize BF_2^+ and one for a source tuned to maximize B atomic ions. Figure 4 contains results of TRIM calculations for which the fractions stated (5 and 10 % relative to the amount of BF_2) of B ions are in the BF_2 and are assumed added to the plasma and accelerated with the bias voltage of 1 keV. This bias corresponds to the 0.22 keV for the shared energy of the B atom in the BF_2 . Clearly these are not totally unrealistic simulations of experimental SIMS profiles for plasma immersion at the bias voltage stated. This result suggests that, despite PAI, some part of the larger junction depths (larger than the “standard”) for the results of Zschätzsch et.al could be due to energy contamination.

Finally, we address the question, as to why the arc results are in such good agreement with the “standard.” First, for the cathodic arc, in one respect it is perfectly reasonable to expect little energy contamination, since the plume is known to consist only of single B atoms. However, at the outset there was a possible issue of some fraction, 11 %, of doubly charged ions (16). Such a fraction would still have been very important as an energy contaminating factor in a “logarithmic” analysis, such as applies for junction depth determination. We have suggested that recombination during transport of the plume could be the reason no effect is detected (3). The samples of Figure 3 were implanted with the targets placed at some 20 cm from the filter.

The next question, as far as cathodic arc is concerned, is why is channeling apparently not the issue that it appears to be for the other PIII or “PLAD” techniques? We believe this result is also related to the amount of transport, in connection with the high ion energy, intrinsic in the cathodic arc plume, as compared with that in gas ion plasmas. Richter et. al. (16) reported the ion energies as near 30 eV (For the plot of Figure 2, we have added 25 eV to the respective bias voltages. Considering the directional issue raised in the present argument, that choice might be questionable, but the analysis is actually hardly sensitive to that choice). The maximum target bias for the arc data was 500 V, as shown. However, since the energy goes as the square of the velocity, the “intrinsic” velocity of the plume ions could have been 20 to 25 % of the added velocity in the acceleration. At the distance of the target, some lateral dispersion was undoubtedly happening due to mutual repulsion of the ions in the high-current beam. The vector velocity of the ions incident on the surface of the Si is the resolved result of that added by the bias in the sheath and that of the intrinsic velocity, which by then, could easily have had enough lateral component to have prevented channeling.

Thus, it is possible that there was an element of good fortune in sample placement in this experiment. At the same time, the position, or a greater distance, is a realistic distance for implantation of actual wafers. If the above hypothesis is true, it may be a somewhat favorable result for the arc technique in some instances. However, we are not assuming that PAI can generally be avoided, even if not needed to limit inward ion transport. That is because of the superior activation of dopants that occurs upon epitaxial regrowth of amorphized Si, in comparison with that which occurs upon annealing of subamorphous damage.

CONCLUSION

Junction depth results for cathodic arc competitive with those of other techniques. Differences and similarities with other techniques are understandable in terms of ion-solid interaction fundamentals pertinent to the respective techniques. Research is continuing, and the cathodic arc concept appears as quite a viable approach to ion implantation issues in advanced miniature circuitry.

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