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Beam Interactions with Materials & Atoms

# Novel beam effect: mass transport due to the lateral component of the ion momentum

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**Abstract**

A new effect in ion beam–solid interaction is described, namely mass transport in the bombarded solid due to lateral momentum transfer from the ions. It manifests itself, after high energy (several MeV) ion implantation at low temperature through a contact mask, as a surface depression at one end, and an elevated surface at the other end of the masked region. It is only evident for off-normal implantations, and then the depressed surface is always on the windward side of the mask and the elevated surface region is always on the downwind side, and it increases superlinearly with ion energy. Electronic stopping effects play a major role not only for the momentum transfer but also for the plastic deformation of the solid.

## 1. Introduction

The basic interaction processes between energetic ion beams and solid targets have been studied for several decades, and one would expect that all the basic ingredients of the interaction have been identified. Surprisingly, this was not so, at least until recently. The majority of structural modifications to the target are due to energy transfer effects, for example, the depth profile of point defects generated during ion bombardment can be estimated by comparing the energy loss of an ion with a threshold energy for Frenkel-pair formation [1]. In addition to these energy transfer phenomena, a few directional effects have been recognized. Examples are the spatial separation between vacancies and interstitials invoked to explain some anomalous defect structures [2], sputtering [3], possibly the unexplained marker shifts during ion beam mixing [4], and the *macroscopic* widening and flattening of metallic glasses in a direction perpendicular to the (GeV) ion beam [5]. The first three examples of changes in the microstructure of the target are thought to be indicative of momentum transfer during a nuclear collision on a *microscopic* scale; the last and macroscopic example is normally explained in terms of Coulomb explosions.

We have recently discovered a directional effect, related to momentum transfer effects, on a *macroscopic* scale [6]. Here, we describe briefly the most important results of our initial investigation of this phenomenon, a more detailed description being in preparation [7].

## 2. Experimental procedures

Ion beams of 6–35 MeV were scanned electrostatically over a $1 \times 1$ cm$^2$ aperture behind which the target was mounted. The target consisted of a piece of material (here: InP, but the effect has been observed in other materials as well) with a smooth surface finish (typically commercially polished and lapped) which was clamped to a liquid nitrogen cooled copper block. On top of the target, a steel contact mask was clamped, with typically $0.3 \times 7$ mm$^2$ rectangular holes through which the ions could hit the target. The target assembly could be rotated (tilted) around an axis perpendicular to the ion beam and in the plane of the target surface. The electrostatic scanner is located about 5 m upstream from the ion implantation chamber, therefore the ion beam can be considered parallel to within 0.11°. Unless otherwise indicated, all implantations were performed at liquid nitrogen temperatures.

Fluxes and fluences were determined by measuring directly the current on target; secondary electrons were suppressed by positively biasing the target and by a negatively biased wire immediately behind the $1 \times 1$ cm$^2$ aperture. For most energies, this yielded current readings equal to those measured in a Faraday cup placed behind the target assembly (of course, the target assembly had to be removed before a current could be measured in the Faraday cup). However, for initial experiments at the highest energies, some secondary electrons were too energetic to

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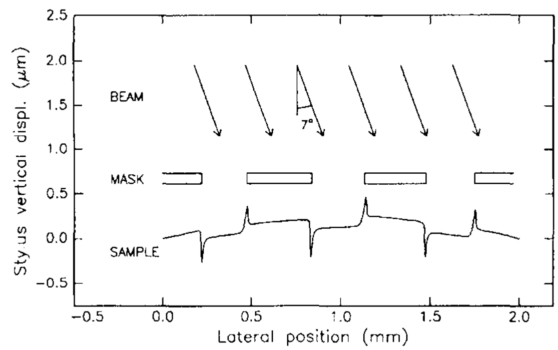


Fig. 1. Surface profile of crystalline InP after implantation with 30 MeV, $10^{15}$ $cm^{-2}$ Se ions through a mask with several openings and with a 7° off-normal direction as indicated.

be suppressed and this led in a few cases to a (suspected) overestimated fluence. We have subsequently used a current reading on a beam profile monitor just before the aperture, which was calibrated against the Faraday cup to measure the current during the highest energy implantations; this gave better reproducibility.

The implanted surfaces were characterized with a stylus profilometer, after removal of the contact mask. A typical surface profile of 3.5 mm of the masked surface covered three periods of alternating bombarded and unimplanted regions. Some samples were studied by scanning electron microscopy (SEM) and energy dispersive X-ray analysis (EDX) but those results are not reported in detail here.

## 3. Surface profilometry: observation of lateral mass transport

Fig. 1 shows the surface profile of a crystalline InP substrate after implantation with 30 MeV Se ions to a fluence of $10^{15}$ $cm^{-2}$, which incidentally is well above the critical fluence for amorphization of the InP. As indicated schematically in the figure, the angle between the ion beam and the surface normal was 7°, in the direction as indicated. Examining the surface profile (bottom curve), a number of observations can be made. First we will discuss observations that can be readily understood based on previous experience: (1) The overall shape shows that the substrate is curved away from the ion beam. This curvature is mostly due to the widening and flattening of the implanted surface region; it is the low energy version of the effect reported in metallic glasses [5]. It has been noticed previously that this effect leads to wafer curvature in Si [8] and InP [9]. (2) The implanted regions are lower than the unimplanted regions. That is because the InP compacts under ion irradiation; the compaction begins during the introduction of defects in the crystalline material and stabilizes when the InP has amorphized [9]. The most striking features of the surface profile, however, are not the overall curvature and the depressed regions, but the appearance of valleys on one side, and peaks on the other side of the openings in the implantation mask. These create a marked asymmetrical shape which we found to have always the same orientation with respect to the angle of incidence of the ion beam.

The first and most obvious explanation that comes to mind for the asymmetrical structure shown in Fig. 1 is a shift towards the right of the entire implanted surface layer due to, and in the direction of, the lateral component of the ion momentum. The valley would then be caused by the physical separation of the implanted region and the unimplanted region windward from the mask opening; the peak occurs when the shifting layer tries to occupy space already occupied by the unimplanted region downwind of the mask opening. This simple explanation now appears to be correct. A few remarks are in order. First, some other possible processes have been eliminated [6], such as the possibility of sputter erosion of the steel mask and subsequent deposition of Fe and Ni near the mask edge, and anomalous behaviour of the profilometer stylus. Second, the real shape of the peak and valley are much more smooth than what appears in Fig. 1, due to the large difference in horizontal and vertical length scale. Third, a series of experiments exploring the evolution of the valley and peak structures as a function of ion fluence, energy, mass, angle of incidence, and flux, gave results that are all consistent with the explanation sketched above. These experiments indicate that the shift is the cumulative effect of rapid deformation of the ion tracks, rather than a slow, rigid shift of the entire layer. Finally, we are dealing with a big effect: for each incident ion (at 30 MeV), about 50 target atoms are moved laterally by about 300 μm.

The first thing to verify is the dependence of the lateral shift on the angle of incidence, for if the shift is indeed due to the lateral ion momentum, it would be non-existing for normal incidence. That is indeed what is observed, as can be seen in Fig. 2, which shows the amount of mass transport as a function of angle $\theta$ between surface normal

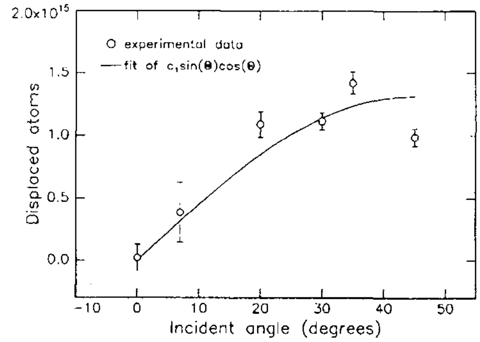


Fig. 2. Total amount of laterally displaced material (along 1 cm perpendicular to the displacement direction), as a function of angle between ion beam and surface normal.

and ion beam; each point measured after identical ion implantation conditions. The line through the data points is a sin $\theta$ cos $\theta$ function; the sin $\theta$ term reflects the component of the ion momentum parallel to the surface and the cos $\theta$ term takes into account the fact that an increasingly shallower layer is being affected as $\theta$ increases. The fact that the data points are well described by a sin $\theta$ cos $\theta$ behaviour supports the explanation of the valley and peak shapes in terms of ion momentum transfer effects.

## 4. Microscopic or macroscopic momentum transfer?

The explanation put forward in the previous section is still a bit vague: the layer does indeed shift in the direction of the lateral component of the ion beam, but by which mechanism? Does microscopic momentum transfer play a major role, systematically leading to a shift between initial and final positions of the recoiled atoms [2]? Or does the collision induced melting near the end-of-range [10] effectively decouple the topmost layer from the substrate, allowing for a rigid shift under the action of the ion beam? Or is perhaps the entire ion track liquefied, deformed, and frozen in a deformed state, all in a few ps? Or, finally, does the ion beam inject so many point defects in the surface layer that as a whole it becomes deformable? The first possibility can be ruled out immediately, simply because the sheer size of the effect is much too big to be caused exclusively by direct, microscopic momentum transfer. To separate between the other possibilities, all involving macroscopic momentum transfer effects, requires more experimental information. Note: With macroscopic momentum transfer, we mean that the ion momentum is transferred to a macroscopic amount of material as a whole, such as an entire ion track or an entire surface layer, rather than to a single atom.

In Fig. 3, we show the amount of lateral mass transport as a function of incident ion energy, all other parameters being kept constant (points). It is seen to increase superlinearly with ion energy. The curves are calculated combining the possible mechanisms sketched above with the known ion energy loss depth profile [6]. If the entire surface layer would decouple from the substrate and rigidly shift, a more or less linear behaviour would be expected (bottom curve). This basically reflects the increase in the total thickness of the shifting layer as the ion energy is increased. Clearly, this does not give a very good fit through the data points. Curves based on the remaining two models describe the data points about equally well. Again, the size of the effect allows us to rule out one mechanism: since the force leading to the shift is only applied during the very short time that the ion slows down, a very low viscosity (similar to that of water) is required to achieve sufficient deformation to fully account for the observed peak and valley sizes. This seems unreasonably low for a defect-induced flow mechanism [11], but appropriate for a description in terms of temporarily liquefied cascade regions [8].

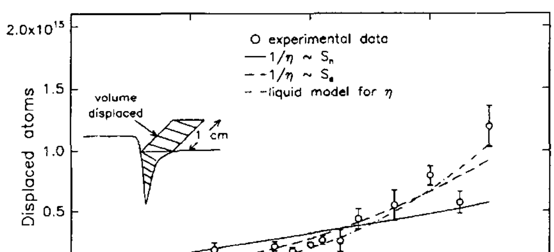


Fig. 3. Total amount of laterally displaced material (along 1 cm perpendicular to the displacement direction), as a function of incident ion energy. Points: experimental data; Curves: calculations according to different possible mechanism.

How does a swift ion transfer its momentum to a rapidly molten cascade, especially in the electronic stopping regime? Consider the following scenario: As the ion moves through the solid, it excites and ionizes many electrons, which slows down the ion. As the electrons fly off in all directions, each carries a certain momentum but the total, net momentum of all excited and ionized electrons has to balance exactly the momentum lost by the ion [12]. The electrons rapidly relax but in the process heat up the ion lattice. The "heating up", of course, involves momentum transfer and again, the ensemble of heated ions will have a total momentum balancing that one lost by the electrons, which balanced that lost by the incident ion. The momentum will eventually be transferred to the sample holder and to the earth, which gains exactly the momentum it lost when the ion was accelerated. Now, if the target is not plastically deformable, no permanent changes occur. But if it is, and if part of the target is liquid, it *is* deformable, some atoms will travel a certain distance before the momentum is transferred, i.e., permanent changes to the target have been made.

## 5. Consequences; is hammering really hammering?

As there appears to be no threshold energy for momentum transfer induced mass transport, other than perhaps an ion energy sufficient for temporal cascade melting, a full description of ion beam–solid interaction is not complete without taking these directional effects into account. And, as ion implantation for opto- and micro-electronic applications has moved well in the MeV energy regime, there are technological implications as well (e.g., anisotropic deformation of implantation masks [13]). It may be recalled that a macroscopic deformation in a direction perpendicular to the ion beam has been observed before, for multi-MeV bombardment of metallic glasses [5] but also for few-MeV implantation of semiconductors [8,9]. There are at least two ways to explain these phenomena in terms of momentum transfer (rather than as Coulomb explosions): (a) When an ion beam is transmitted by a thin film, the transmitted beam has a slightly larger divergence than the incident beam. This implies that the recoils and excited electrons left behind in the sample have acquired substantial momentum in the plane perpendicular to the ion beam. This could lead to a deformation as observed. Or, (b), the ion track, temporarily liquefied, is squeezed between hammer (the incident ion) and anvil (inertia of the underlying substrate). In the last scenario, the Klaumünzer effect, which is sometimes known as the hammering effect, would really be a hammering effect.

## 6. Conclusion

We have observed a striking deformation in the surface region of some targets subjected to high energy ion implantation in off-normal directions. It appears to be due to transfer of the lateral component of the ion momentum. The most likely mechanism appears to involve melting of the entire ion track on a sub-ps time scale, in the nuclear stopping as well as in the electronic stopping regime. The high-temperature, low viscosity liquid then deforms and freezes in the deformed state. The cumulative effect of continued implantation is a directional deformation of the entire surface layer.

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