RADIATION-ENHANCED PLASTIC FLOW OF COVALENT MATERIALS DURING ION IRRADIATION

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ABSTRACT

Plastic deformation of several covalently-bound materials has been studied during ion irradiation. In all of these materials, namely crystalline and amorphous silicon, crystalline and amorphous $Si_{0.9}Ge_{0.1}$, and amorphous SiO_2, the damage created by the ion beam causes density changes in the irradiated region which eventually saturate with ion dose. In the crystalline materials, the density changes were accompanied by a transformation to the amorphous phase. Superimposed on the density changes is plastic deformation which occurs during irradiation of both crystalline and amorphous materials to relieve stresses in the irradiated region. A wafer curvature measurement technique has been developed which allows the contributions from density changes and plastic deformation to be distinguished and the stress dependence of the plastic deformation to be determined.

In all of the amorphous materials, the plastic deformation is Newtonian viscous shear flow, which is characteristic of solids where deformation is governed by the diffusive motion of point defects. The radiation-enhanced shear viscosity per ion was flux-independent, revealing that flow occurs rapidly, probably within the localized damaged regions created by each ion. This viscosity does not depend strongly on the material. In fact, similar viscosities were obtained during measurements of radiation-enhanced plastic deformation of crystalline covalent samples and polycrystalline aluminum films.

INTRODUCTION

Ion irradiation is a widely used technique for the modification and doping of surface layers of semiconductors, insulators, and metals. During irradiation, damage is created in the near-surface region leading to morphology changes and deformation. This behavior has been extensively studied in metals and has led to the observation of radiation-enhanced creep and viscous flow. Recently, radiation-enhanced deformation has been observed in covalently-bound materials such as amorphous Si [1] and SiO_2 [2]. In these studies, measurements were made for irradiation energies between 150 keV and 3 MeV. At much higher energies (several hundred MeV or higher), anisotropic plasticity of a wide range of amorphous materials has been reported [3,4], which is attributed to large stresses in densely ionized regions. This effect is expected to be negligible at the energies used in this study and, unlike the results presented here, exhibits a dependence on the ion beam direction. In this paper we will present new measurements on radiation-enhanced deformation in crystalline and amorphous Si, amorphous SiO_2, and crystalline and amorphous SiGe alloys. A comparison will be made with recent measurements of radiation-enhanced deformation in polycrystalline Al films.

The studies presented here were made using in-situ wafer curvature measurements during ion irradiation, which are extremely sensitive to both density changes and plasticity. A simple procedure has been recently developed which allows the contributions from density changes and plasticity to be distinguished and the stress dependence of the plasticity to be determined. This procedure involves "setting" the samples in a range of stress states by irradiating or annealing them while they are clamped to differently curved armatures. After release from the armatures and during subsequent irradiation, the stress dependence of the plastic deformation can be determined and separated from density changes. This paper presents a summary of some of these results. It is concluded that plastic deformation in amorphous covalent materials is due to atomic rearrangements that occur in highly damaged regions created by each ion. The plastic deformation in crystalline covalent materials and polycrystalline aluminum films is comparable in magnitude.

EXPERIMENTAL TECHNIQUE

Experiments were performed on a variety of samples: crystalline Si (c-Si), amorphous Si (a-Si), amorphous SiO_2 (a-SiO_2), crystalline and amorphous SiGe alloys, and polycrystalline Al. The SiO_2 films (5100 Å thick) were deposited on one side of a (100) Si wafer by plasma-enhanced chemical vapor deposition (PECVD) and then annealed at 1000 °C for one hour in a vacuum furnace to allow them to relax and densify [5]. The $Si_{0.9}Ge_{0.1}$ films (7100 Å thick) were deposited on (100) Si at 550 °C using molecular beam epitaxy. The aluminum films (5500 Å thick) were deposited by evaporation at room temperature onto 5000 Å thick a-SiO_2 layers on Si. In all cases, the samples were small rectangles (0.3x2.5 cm^2) cleaved from double-side polished, undoped, (100) silicon wafers between 75 and 200 μm thick. Film thicknesses were measured using Rutherford backscattering spectrometry (RBS).

Ion implantation was performed with a variety of ions and a range of fluxes (1×10^{10} ions/cm^2 to 1×10^{12} ions/cm^2), and the ion energies were chosen so that the maximum depth of the ion beam damage was within the deposited films. Each sample was clamped by one end to a temperature-controlled copper block in the ion beam chamber, leaving the other end free to bend. All of the experiments presented here were performed on samples held within ± 30 °C of room temperature. The ion beam was rastered through a 0.5x1.1 cm^2 aperture that defined a stripe across the sample.

In-situ measurements of the stress in the irradiated region of a sample during ion implantation were made using a wafer curvature apparatus. The sample curvature was measured using a scanning laser reflection technique [1], in which a He-Ne laser beam was scanned up and down the back surface of the sample while it was implanted from the front. The curvature was determined from the orientation of the sample surface as measured by the angle of the reflected laser beam. For samples where the thickness of the irradiated region, t_i, is much less than the wafer thickness, t_o, the integrated stress, S, in the plane of the irradiated region of the film can be calculated from the measured radius of curvature, R, [6],

$$S = \int_0^{t_i} \sigma(x)\,dx = \frac{Y_o t_o^2}{6R} \qquad (1)$$

where $\sigma(x)$ is the local in-plane stress at a depth x, and Y_o is the biaxial stress state elastic modulus for the (100) silicon substrate. Y_o is equal to $E_o/(1-\nu_o)$, where E_o is Youngs modulus and ν_o is the Poisson ratio, and is isotropic in the (100) plane [7]. Because the damage created by the ion beam is depth dependent, the local stress will be different from the average in-plane stress, which is given by S/t_i. For the samples used in this study, vibrations in the ion beam line limited the resolution of the integrated stress to ± 0.5 N/m. The absolute determination of the integrated stress is limited to ± 25 N/m due to local variations in wafer and film thicknesses which produce an offset of the measured curvature of a given sample. Scans typically required 0.3 seconds, and were repeated every second. Compressive stresses are presented as positive values and tensile stresses as negative values.

There are two possible contributions to stress changes during irradiation: density changes and plastic shear deformation. Density changes result from ion beam-induced morphology changes whereas plasticity occurs in response to the stress in the film. In the case that the plastic deformation is Newtonian shear flow (strain rate proportional to the stress), the change in integrated in-plane stress with dose, ϕ, is given by [1],

$$\frac{dS}{d\phi} = \frac{-Y_i t_i}{3}\frac{d}{d\phi}\left(\frac{\Delta\rho}{\rho_o}\right) - \frac{Y_i}{6\dot{\phi}\eta}(S - S_{yd})\,. \qquad (2)$$

The first term on the right indicates the effect of density changes, $\Delta\rho/\rho_o$, and the second term the effect of plastic flow on the integrated in-plane stress. η is the Newtonian shear viscosity and $\dot{\phi}$ is the flux. Y_i is the biaxial stress state elastic modulus of the irradiated region. Although it is known that Y_i changes considerably during amorphization [8], it can be assumed constant once amorphization is complete. The values of Y_i used in this study were 1.35×10^{11} N/m^2 for a-Si [8,9], 1×10^{11} N/m^2 for a-SiO_2 [10], and 1.78×10^{11} N/m^2 for $Si_{0.9}Ge_{0.1}$ [11]. The possible

existence of a yield stress, S_{yd}, which is the minimum stress required for plastic deformation, has been included.

If $dS/d\phi$ is measured for a single sample, $\Delta\rho/\rho_0$ and η can not be determined independently. Therefore measurements were performed on several samples prepared in different stress states but with the same thermal and implantation history. This was accomplished by irradiating or annealing samples clamped to various cylindrically curved armatures. If plastic flow occurs during irradiation or annealing, then the samples should have different curvatures, or stresses, when released from the differently curved armatures. The change in stress during subsequent irradiation was then measured for each of these samples and the (stress-independent) density changes and (stress-driven) flow contributions could be separated [12]. In the following sections, this procedure is used for measurements on Si, SiO_2, $Si_{0.9}Ge_{0.1}$, and Al. For each material we first present the integrated in-plane stress during irradiation of the as-prepared samples. Then we present the results for samples set in different initial stress states. These results are analysed to check for Newtonian behavior and to determine the density changes and the radiation-enhanced shear viscosity.

RESULTS

Si

The integrated in-plane stress, S, during amorphization of Si with 2 MeV Xe is shown in Figure 1. As the sample is irradiated, the surface region expands, creating a compressive stress (S>0) in the irradiated region (1.45 μm thick) and bending the wafer away from the irradiated surface. The stress reaches a maximum, then decreases with dose and finally saturates at a small compressive value of roughly 30 N/m. The details of this behavior have been studied in a previous investigation [1]. The initial stress increase is caused by expansion due to the creation of damaged crystal. The stress maximum is reached just as amorphous regions are formed, and decreases as more amorphous material is formed, finally saturating at a non-zero stress with the formation of a continuous amorphous surface layer. Based on the results of two different types of experiments, the stress decrease has been attributed to radiation-enhanced plasticity [1], which

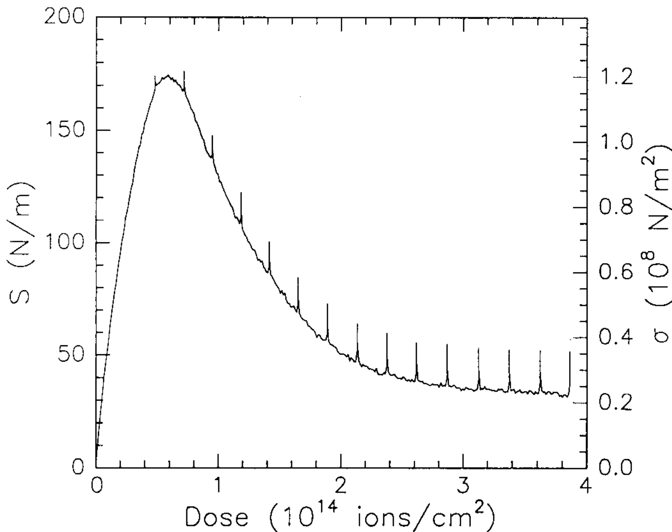

Figure 1: Integrated in-plane compressive stress in Si during amorphization with 2 MeV Xe. The vertical spikes show the effect of beam interruption. The average compressive stress in the implanted region is indicated on the right-hand axis.

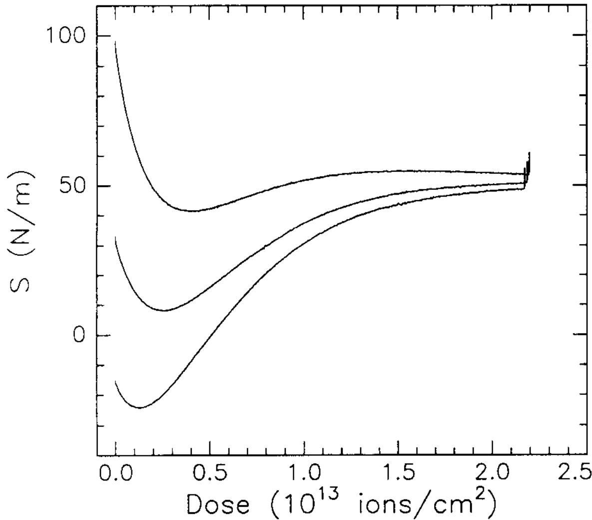

Figure 2: Integrated in-plane stress in the irradiated region of 2.1 μm thick a-Si layers during irradiation with 2 MeV Xe. The samples were set in different stress states prior to irradiation by annealing them at 500 °C for 1 hour while clamped to cylindrically curved armatures.

moves atoms to the surface of the irradiated region in order to relieve the in-plane stress. The final, non-zero stress is identified as a yield stress for flow. It is larger for lighter ions [13], suggesting that it depends on the nature of the damage created by irradiation, rather than on the material. The vertical "spikes" in Figure 1 show the effect of 30 second interruptions of the ion beam: when the ion beam is turned off the stress increases due to the expansion of the implanted region; when the beam is turned on again the sample densifies and the stress returns to the value it had just prior to beam interruption. This beam-reversible density change is due to room temperature structural relaxation of a-Si [14].

Further evidence for the existence of radiation-enhanced plastic deformation in a-Si is shown in Figure 2. a-Si layers (2.1 μm thick) made by multiple-energy Si implantation (0.5, 1.0, and 2.0 MeV) of c-Si [15] were clamped in various stress states, both tensile and compressive, and annealed in a vacuum furnace at 500 °C for 1 hour. This anneal causes density changes and plastic flow [14,16], structural relaxation [17], and a small amount of recrystallization at the buried interface [18]. The plastic flow causes the samples to take a "set" stress dependent on the curvature of the armature. The samples were then unclamped and implanted with 2 MeV Xe at a dose rate of 1×10^{11} ions/cm^{2}s. The stress in the 1.45 μm thick Xe irradiated region of the a-Si is shown in Figure 2 for three different samples. The initial stresses are the different "set" stresses. The fact that the stress changes during irradiation of each sample are different indicates they are stress-dependent and thus due to plasticity which is radiation-enhanced since it only occurs when the ion beam is present.

The strain rate ($d\varepsilon/dt$) versus the stress for the three samples in Figure 2 is shown in Figure 3. At a given dose, each data point represents one of the three samples. The strain rate is obtained from the slope of the curves in Figure 2: $d\varepsilon/dt = (\dot{\phi}/Y_i t_i)(dS/d\phi)$. As can be seen in Figure 3, the strain rate and the stress are linearly related, indicating that equation (2) is an appropriate description of density changes and plastic flow during ion irradiation of a-Si. By performing the analysis shown in Figure 3 using linear least squares fitting, the density changes and Newtonian shear viscosity can be determined as a function of dose. Figure 4(a) shows the density change during irradiation: the sample first compacts and then expands yielding a final density increase of

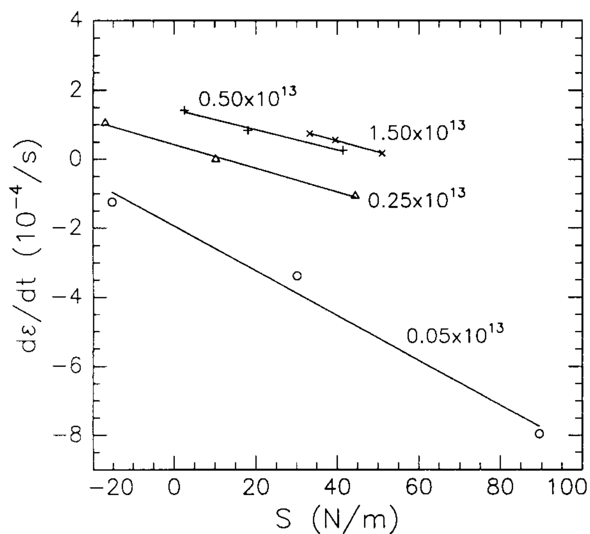

Figure 3: Average strain rate versus the integrated in-plane stress for the samples shown in Figure 2 at several different doses. At a given dose, each data point corresponds to a single sample.

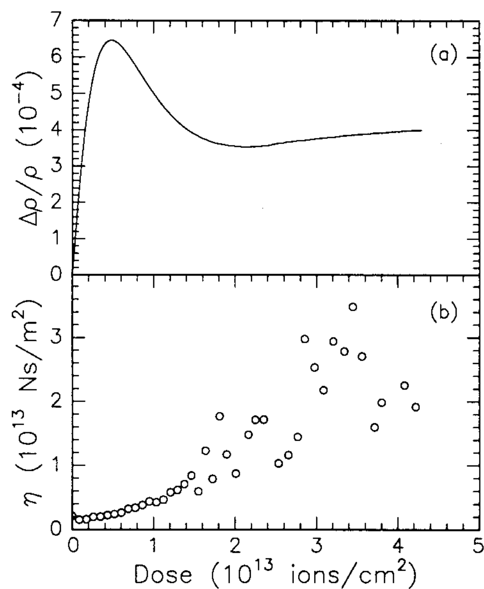

Figure 4: (a) Density change and (b) Newtonian shear viscosity during 2 MeV Xe irradiation of a-Si layers previously relaxed at 500 °C.

0.04 %. When the ion beam is turned off, the amorphous silicon expands by 0.04 % (the cause of the "spikes" in Figure 1 and at the end of the implants in Figure 2), so the net density change in the bombarded region is zero. It is interesting to note that relaxation by heating a-Si causes both expansion and densification, but the net density change is also zero [14]. This supports the observation that ion irradiation reverses structural relaxation [17]. The shear viscosity is shown in Figure 4(b); it is initially $2x10^{12}$ Ns/m^2 and increases to roughly $2x10^{13}$ Ns/m^2 during irradiation.

Radiation-enhanced plastic flow has also been observed in c-Si using a similar experimental procedure. In this case, c-Si samples were clamped to the cylindrically curved armatures and irradiated at room temperature with low doses, to avoid amorphization. Even for doses as low as $5x10^{12}$ 2 MeV Xe/cm^2, which corresponds to roughly one in 50 atoms being displaced by nuclear collisions (no lower doses were investigated), this procedure produced samples in which the stress state varied substantially with the curvature of the armature. No stress was produced in ion-beam damaged samples that were clamped but not irradiated, indicating that thermally-activated flow in damaged c-Si is negligible at room temperature.

a-SiO_2

Results during irradiation of a-SiO_2 films are shown in Figures 5 through 7. All of the stresses are presented as ΔS which is the measured stress minus the final stress, S_o. The final stress ($S_o \leq 25$ N/m) includes contributions from the buried unirradiated region of the SiO_2 film, a possible yield stress in the irradiated region, and an uncertainty due to variations in wafer thickness. The change in stress during 150 keV Si irradiation at room temperature of an a-SiO_2 film is shown in Figure 5. The dose rate was $3x10^{12}$ $ions/cm^2s$. The initial stress is set during the 1000 °C anneal. It results from densification and flow of the film at 1000 °C and the fact that the thermal expansion coefficient of SiO_2 is smaller than that of silicon, which drives the stress compressive during cooling to room temperature. As the sample is irradiated, the stress decreases, changing from compressive to tensile. It reaches a minimum value of 70 N/m and then increases and finally saturates. A rough estimate of the average stress in the irradiated region is shown on the right-hand axis: it was obtained by dividing the integrated stress by the thickness of the irradiated region which was estimated as 4000 Å using TRIM '88 simulations [19]. Unlike a-Si, there are no beam-reversible density changes in a-SiO_2 associated with turning the ion beam

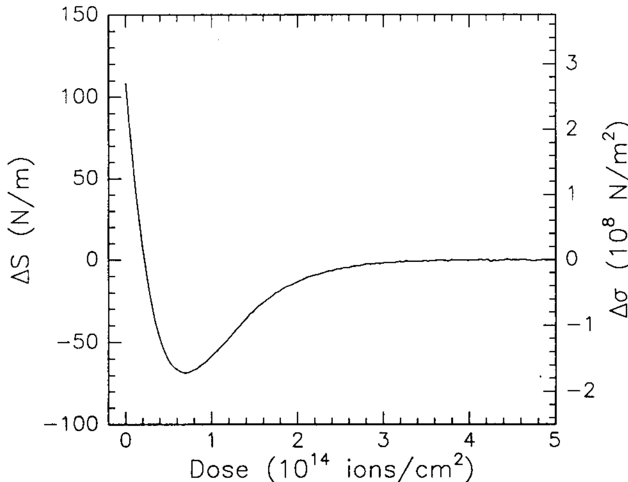

Figure 5: Change in the integrated in-plane stress in a 5100 Å thick SiO_2 film on silicon during implantation with 150 keV Si. The average stress in the implanted region is indicated on the right-hand axis. Positive stresses are compressive.

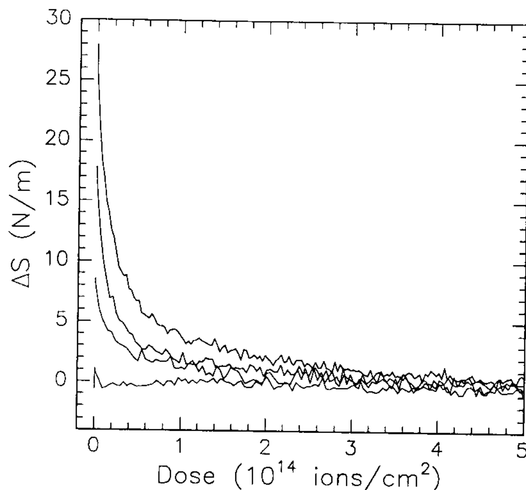

Figure 6: Change in the integrated in-plane stress in 5100 Å thick SiO_2 films on silicon during implantation with 150 keV Si. The four samples were first set in different stress states by irradiating them with $1x10^{15}$ 150 keV Si/cm^2 while clamped to different cylindrically curved armatures.

on and off.

By comparing these measurements with studies of densification as measured from changes in the refractive index [20,21], the initial stress decrease can be attributed to densification [22], whereas the subsequent increase occurs without a density change. Similar to the case for silicon, in order to explain a stress change without a density change, shear deformation must occur. The idea of plastic deformation was tested by clamping four SiO_2 samples to various cylindrically curved armatures and irradiating them with 150 keV Si to a dose of $1x10^{15}$ ions/cm^2, which according to Figure 5 is more than sufficient to allow for stress changes. Since no curvature is induced in samples clamped to an armature for a similar length of time without being irradiated, any flow that occurs must be radiation-enhanced. The different stress states of the four a-SiO_2 films, once they had been removed from the clamps, are indicated by the initial stresses in Figure 6, which shows the results during subsequent 150 keV Si implantation at $1x10^{12}$ ions/cm^2s. The stresses in these samples decreased with dose and eventually saturated. The strain rate versus stress for the four samples is shown in Figure 7 at several different doses. Each data point represents one sample and was obtained by determining the strain rate, or $dS/d\phi$, and the integrated stress of each sample at a given dose. There are several important features of the data in Figure 7: the flow is Newtonian (strain rate and stress are linearly related), there is no density change (y-intercept is zero), and the viscosity increases (slope decreases) with dose, from $1x10^{12}$ Ns/m^2 to $4x10^{12}$ Ns/m^2. The fact that the viscosity increases with dose even though the SiO_2 density does not change and the mechanism for flow remains Newtonian, is a surprising and interesting result.

Similar measurements were performed during irradiation of SiO_2 with 800 keV Au [2]. The behavior was quite similar to that shown in Figure 5 and 6 except that the viscosity remained constant with dose. In addition, the measurements revealed that the flow per ion was flux-independent for fluxes in the range $1x10^{10}$ to $1x10^{12}$ ions/cm^2s. This means that each ion contributes independently to flow and that the quantity of interest is $\eta_{rad} = \dot{\phi}\eta$ rather than η. For irradiation of SiO_2 with 800 keV Au, η_{rad} is $5.3x10^{22}$ (N/m^2)(ions/cm^2), independent of the flux.

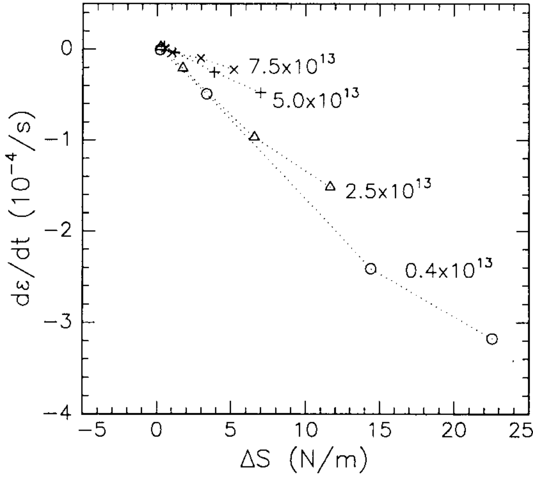

Figure 7: Average strain rate versus the integrated in-plane compressive stress for the samples shown in Figure 6 at several different doses. At a given dose, each data point corresponds to a single sample.

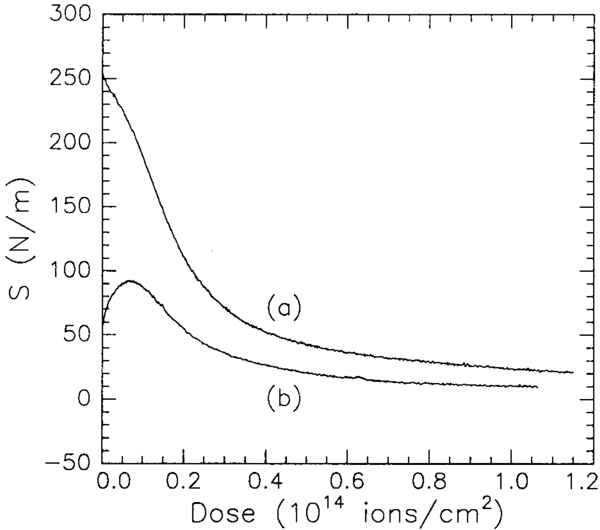

Figure 8: Integrated in-plane stress during 700 keV Xe irradiation of 7100 Å thick $Si_{0.9}Ge_{0.1}$ films. Sample (a) is an as-deposited hetero-epitaxial film, sample (b) had previously been annealed to 900 °C to for allow stress relaxation by the formation of misfit dislocations at the interface.

$Si_{0.9}Ge_{0.1}$

The in-plane integrated stresses in the bombarded region of two 7100 Å thick $Si_{0.9}Ge_{0.1}$ films on silicon are shown in Figure 8 during implantation at room temperature with 700 keV Xe at a dose rate of $7x10^{10}$ ions/cm^2s. Sample (a) is an as-grown hetero-epitaxial film. Sample (b) has been annealed in a vacuum furnace to 900 °C. This anneal is known to cause stress relaxation by the introduction of misfit dislocations at the interface [11]. The ion energy was chosen to keep the damage well away from the buried interface, at a maximum depth of 5000 Å. Both samples undergo stress changes during bombardment which eventually saturate. For sample (a) the stress monotonically decreases, whereas for sample (b) the stress first increases and then decreases. The stress changes of sample (b) are qualitatively similar to those of pure silicon (Figure 1). This suggests that the addition of 10 % Ge does not have a large effect on the ion beam interactions with the solid. RBS channeling measurements show that the stress maximum is reached just as amorphous regions are formed ($6x10^{12}$ ions/cm^2). Therefore, the stress increase of sample (b) is attributed to expansion due to the creation of damaged crystal, while the decrease is due to plasticity. As for pure silicon, a yield stress for flow is observed (~ 10 N/m). Although not shown in Figure 8, SiGe also exhibits a beam-reversible density change like pure silicon. In contrast to sample (b), the stress in sample (a) decreases even while the sample is expanding from the creation of damaged crystal. This indicates that radiation-enhanced flow occurs easily in the crystal. Although the stress dependence of the flow in c-SiGe is not known and two samples are not sufficient for its determination, an estimate of the contribution from plasticity can be made using equation (2). The Newtonian shear viscosity, as estimated, remains fairly constant at $5x10^{12}$ Ns/m^2 during amorphization and then increases to $4x10^{13}$ Ns/m^2.

Al

For the purpose of comparing radiation-enhanced flow in covalent materials with the well known process of radiation-induced creep of metals, measurements were performed during ion irradiation of aluminum films. Results are shown in Figure 9 for irradiation at room temperature with 700 keV Xe at a dose rate of $7x10^{10}$ ions/cm^2s. Sample (a) is an as-evaporated film, sample

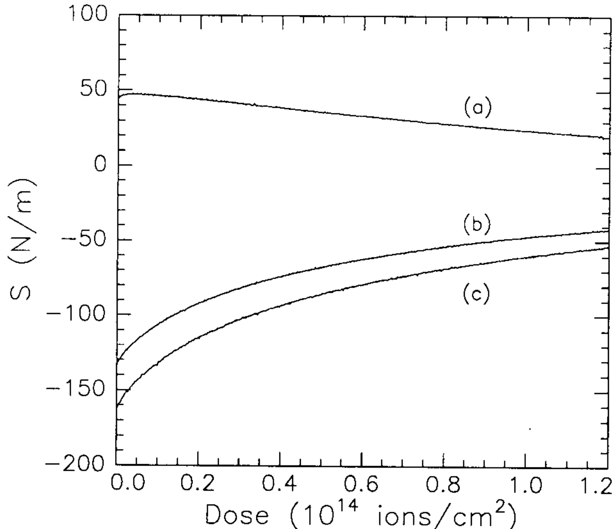

Figure 9: Integrated in-plane stress in the irradiated region of 5500 Å thick Al films on SiO_2 on Si during 700 keV Xe irradiation. Sample (a) is an as-evaporated film, samples (b) and (c) had been annealed to 360 °C.

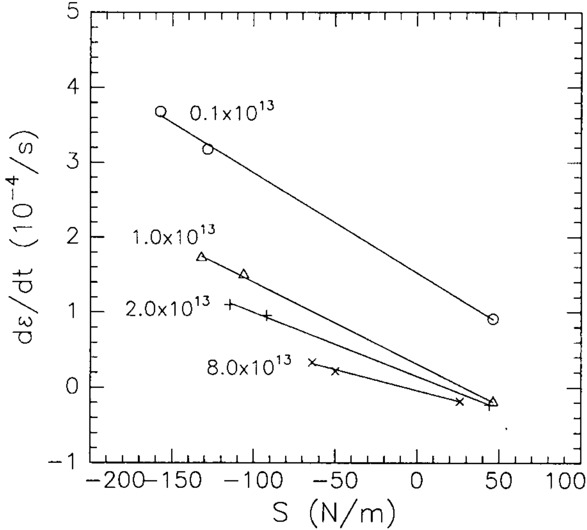

Figure 10: Average strain rate versus the integrated in-plane stress for the Al films shown in Figure 9 at several different doses. At a given dose, each data point corresponds to a single sample.

(b) has been heated to 360 °C while clamped to an armature, and sample (c) was heated to 360 °C while free to bend. This anneal is expected to cause some grain growth and allow for stress relief by thermally-activated plasticity of the film. Due to the large difference between the thermal expansion coefficients of aluminum and silicon, cooling samples (b) and (c) from 360 °C creates a large tensile stress in the aluminum [23]. During irradiation, the stresses in the samples

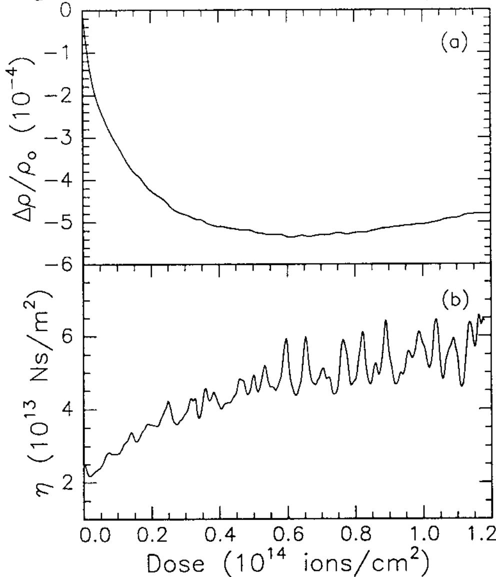

Figure 11: (a) Strain due to stress-independent contributions and (b) Newtonian shear viscosity during 700 keV Xe irradiation of Al films on SiO_2 on Si.

decrease. In addition to radiation-enhanced creep, there may be contributions from changes in the yield stress and irradiation growth [24]. If all of these contributions are assumed stress-independent, then an estimate of the contribution from plastic flow can be made. This is illustrated in Figure 10 which shows the results of an analysis similar to that described before. As can be seen, the strain rate and stress are again linearly related, indicating that equation (2) is an appropriate description of the irradiation-induced changes in the Al. Figure 11(a) shows the strain produced by possible contributions from density changes, irradiation growth, and the yield stress. Figure 11(b) shows the shear viscosity during irradiation. It increases slightly during irradiation, from $2x10^{13}$ Ns/m^2 to $6x10^{13}$ Ns/m^2.

SUMMARY and DISCUSSION

All covalent materials that were studied exhibited irreversible density changes due to the creation of ion beam damage. Only a-Si and a-SiGe showed beam-reversible density changes. Earlier measurements have shown that these changes in a-Si are due to room temperature structural relaxation. The fact that structural rearrangements occur at room temperature in a-Si and a-SiGe, while they do not occur in a-SiO_2, suggests that either atomic rearrangements are easier or the ion beam-induced damage is less stable in Si and GeSi than in SiO_2.

All of the amorphous materials exhibited Newtonian viscous shear flow. This is expected in solids where the flow is governed by the diffusive motion of point defects. The values of the radiation-enhanced viscosity per ion, η_{rad}, are summarized in Table I for all of the materials presented in this study. The wide range in the value of the viscosity for each sample reflects the change in the viscosity during irradiation. For reference, the calculated [19] average number of displacements per atom (dpa) for irradiation with 10^{14} ions/cm^2 is shown in Table I for each material. Because of this large change in the viscosity of each sample during irradiation, it was not possible to correlate these numbers with various quantities such as estimates for the nuclear damage densities. All radiation-enhanced viscosities are in the range $2x10^{23}$-$4.2x10^{24}$ (N/m^2) (ions/cm^2), except the result for 800 keV Au irradiation of SiO_2. It is interesting to note that this was the only experiment where the viscosity remained constant during irradiation. It is quite remarkable that the radiation-enhanced viscosity for Al is similar to that of the covalent materials, which suggests a material-independent mechanism for flow. The fact that in most cases the viscosity increases during irradiation, even once the density changes have saturated, is surprising and needs further investigation. A possible explanation is that a certain type of damage is created during irradiation which does not produce a density change. The change in viscosity during irradiation of Al may be due to radiation-induced morphology changes such as grain growth.

The amount of flow per ion in the amorphous covalent materials is flux independent. If we assume that a typical collision cascade region has a diameter of 100 Å we can estimate that, for the fluxes investigated, each region gets ion-damaged every 1 to 100 s. Thus, the flow must occur in

Experiment	dpa (/10^{14} ions/cm^2)	$\dot{\phi}$ (ions/cm^{2}s)	η (Ns/m^2)	η_{rad} (N/m^2)(ions/cm^2)
2 MeV Xe -> a-Si	0.4	$1x10^{11}$	$(2\text{-}20)x10^{12}$	$(2\text{-}20)x10^{23}$
150 keV Si -> SiO_2	0.08	$1x10^{12}$	$(1\text{-}4)x10^{12}$	$(1\text{-}4)x10^{24}$
800 keV Au -> SiO_2	0.5	$1x10^{10}$	$5.3x10^{12}$	$5.3x10^{22}$
		$1x10^{11}$	$5.3x10^{11}$	$5.3x10^{22}$
		$1x10^{12}$	$5.3x10^{10}$	$5.3x10^{22}$
700 keV Xe -> $Si_{0.9}Ge_{0.1}$	0.6	$7x10^{10}$	$(5\text{-}40)x10^{12}$	$(3.5\text{-}2.8)x10^{23}$
700 keV Xe -> Al	0.3	$7x10^{10}$	$(2\text{-}6)x10^{13}$	$(1.4\text{-}4.2)x10^{24}$

Table I: Ion fluxes, Newtonian shear viscosities, and radiation-enhanced viscosities per ion for the materials and irradiation conditions discussed in this paper. The calculated average number of displaced atoms (dpa) for an irradiation fluence of 10^{14} ion/cm^2 is also indicated.

less than one second. It is therefore believed that the plastic flow occurs in localized highly damaged regions produced by each ion.

The final, non-zero stresses observed during amorphization of a-Si and a-SiGe indicate the existence of a radiation-enhanced yield stress in these materials. Due to uncertainties in the absolute value of the stress, the existence of a radiation-enhanced yield stress in a-SiO_2 can not be ruled out. Yield stresses are not typically observed during thermally-activated flow of amorphous materials. It is possible that they are due to the existence of a stress-dependent critical damage density required for flow. This conjecture is supported by the observation that the yield stress in a-Si is larger for lighter ions

In summary, radiation-enhanced plastic deformation has been observed in crystalline and amorphous covalent materials. In the amorphous state, this deformation is Newtonian viscous and is governed by atomic motion in the highly defective regions produced by each ion. The Newtonian shear viscosity per ion does not depend strongly on the particular material and is therefore expected to be an ubiquitous effect.

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