Amorphous silicon deposited by xenon ion beam assisted deposition

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Abstract

In this work, we present some properties of amorphous silicon deposited by ion beam assisted deposition (IBAD). The films were prepared using a Kaufman ion gun using xenon (Xe) gas to sputter a silicon target. Another ion gun was adopted to simultaneously bombard the film with Xe during the growth of the film with xenon in the 0–300 eV energy range. Rutherford backscattering (RBS) was used to determine the concentration of the implanted Xe atoms and the density of the films. It was observed that the implantation of Xe do not affect much the stress of the films, which is compressive and about −0.6 GPa for all samples. The concentration of implantation Xe reach a maximum at energy of about 50 eV decreasing as the ion energy increases. The density of the films follows the concentration of Xe, suggesting that the densification of the film is not due to a compactation process supplied by the Xe bombardment of the films, but rather due to the incorporation of a heavy atom into the matrix.

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1. Introduction

Amorphous silicon has been developed by a number of techniques aiming to achieve high quality films. Usually, hydrogen is incorporated to reduce defects. However, the hydrogen itself has been responsible for the film instability [1]. Ion beam assisted deposition had been proposed as an alternative technique to reduce defects, by a controlled bombardment of the films during growth with argon atoms [2]. The incorporation of unwanted argon atom into the films also creates dangling bonds due to the bombardment of the film. Ion bombardment with noble gas has also been used for etching, surface cleaning, and depth profiling. Molecular dynamics has been used to investigate the effect of dose implantation [3], mechanical properties [4], stress [5] structural properties [6] among other investigations [7–11]. Some works have investigated the incorporation of noble gases. The basic difference between IBAD and conventional implantation refers to the energy used, which is much smaller for the IBAD technique. In this work we investigate amorphous silicon, a-Si, films deposited by ion beam assisted deposition, using Xe ion as assisting atom during the growth of the film.

2. Experimental

Amorphous silicon films were prepared by ion beam assisted deposition (IBAD) using two Kaufman sources, one for sputtering a silicon target, and the other used to simultaneously bombard the films during growth. A series of films, of about 0.3 µm thick, was deposited at 150 °C, in the 0–300 eV range. The chamber base pressure was 1 × 10⁻⁶ mbar, and the deposition pressure was ~5 × 10⁻⁴ mbar. The crystalline silicon target was bombarded by a xenon ion beam with 1500 eV. Stress measurements were performed in films deposited on c-Si ⟨1 1 1⟩ 4 × 25 × 0.4 mm³ bars, using the bending beam method [12]. RBS measurements were used to determine the density of the

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films, using standard procedure, considering the thickness obtained by a dektak profilometer.

3. Results

Fig. 1 shows that the deposition rate decreases dramatically as the assisting energy increases. For films prepared with assisting energy of 300 eV, the deposition rate is close to zero. This behavior hinders the deposition of films under higher assisting energy. Beside the sputtering process some xenon atoms are incorporated into the films, as revealed by Rutherford backscattering, RBS. Fig. 2 displays the concentration of xenon as a function of the ion assisting energy obtained from RBS. It shows that the Xe concentration reaches a maximum at about 50 eV and decrease to nearly zero at 300 eV.

The density of the films, Fig. 3, was obtained through RBS measurements. As can be observed the behavior of

![Fig. 1. Deposition rate of a-Si films as a function of the assisting energy for films deposited by IBAD using Xe as assisting atom.](image)

![Fig. 2. Xe concentration, as a function of the assisting energy, for a-Si films deposited by IBAD using Xe as assisting atom.](image)

![Fig. 3. Density of a-Si films as a function of the assisting energy for films deposited by IBAD using Xe as assisting atom.](image)

![Fig. 4. Density of a-Si films as a function of Xe concentration for films deposited by IBAD using Xe as assisting atom.](image)

![Fig. 5. Stress as a function of the assisting energy for a-Si films deposited by IBAD using Xe as assisting atom.](image)
the density and concentration, as a function of assisting energy, are similar, Figs. 2 and 3, such that one is attempted to correlate the density of the films with the concentration of xenon. Fig. 4 shows this relation, indicating that the density depends on the concentration of xenon, as expected.

The incorporation of xenon do not affect significantly the stress of the films, Fig. 5, even though a compressive stress is observed for all of them, been of about −0.6 GPa except for the film deposited under 0 eV of assisting energy.

4. Discussion

The reduction of the deposition rate, Fig. 1, is due to the sputtering process caused by the bombardment of the assisting xenon atoms. This effect increases as the energy increases in the range of energy investigated. A similar behavior has been reported for other materials, such as amorphous carbon [13].

The simultaneous bombardment of xenon, while the silicon films have been deposited, works as a highly efficient implantation process under very low energy as compared with conventional implantation, which requires tens of thousand of electron volts. In Fig. 2 one can observe that it is required only few tens of electron volts to achieve an incorporation of about 5 at. % of xenon, which is about the same range of concentration obtained by conventional implantation. In addition, using IBAD one can obtain a uniform distribution of noble gases in the film, which is very difficult to obtain by conventional implantation.

The incorporation of xenon is relatively high, reaching about 5.5%, which is close to the solubility limit of about 9%. It has been observed that the probability of implantation of gases through conventional implantation process increases as a function of energy and reaches a saturation regime at certain energy indicating a limit of solubility of noble gases into the matrix [14]. No clear evidence of saturation was observed in our work, such that it is likely that one can achieve higher concentration of xenon into the films under condition not explored yet.

The bombardment energy could, in principle, promote a densification of the film structure, such as that reported for a-C [15]. Craigen and Brodie [2] also studied a-Si by IBAD, but bombarding the films with argon atoms and got an increase in the film density, reaching up to 2.38 g/cm³, slightly higher than the density of crystalline silicon (2.33 g/cm³). They attributed the increase in the density of the film to an effective process to improve the film structure by reducing voids through the bombardment process. However, considering Fig. 4, it is very likely that the increase in the density of our a-Si films as well as of those reported by Craigen and Brodie is due to the incorporation of atoms (Xe and Ar) heavier than the silicon atoms, instead of a densification of the film structure only. However, one can not disregard that the ion bombardment can, in principle, promotes some reduction in the density of voids in the films.

Molecular dynamics study shows that the incorporation of gas interstitially into the network should introduce a compressive stress into the film [6]. In fact, this phenomenon has been observed in TiN films [16]. Our films are compressive, ~0.6 GPa, probably due to the incorporation of xenon atoms. However, within experimental error, there is no correlation between stress and the concentration of xenon, see Fig. 5. Thus, since the increase in the xenon concentration does not increase the stress, it is likely that xenon atoms are incorporated in voids. However, the considerable increase in the density of the films suggests that the xenon atoms are isolated, instead of clustered, in most of our films. The reason we propose this arrangement is because fcc solid xenon has a density of 5.9 g/cm³, which is about 2.5 times the density of silicon. However, xenon atoms are about 5 times heavier than silicon atom, such that isolated atoms could be more effective in increasing the density of the films than xenon incorporated in the form of clusters.

As we observed in Fig. 2, there is an energy in which the incorporation of xenon is more efficient. Similar behavior have been observed in the stress of amorphous carbon films deposited by the same technique, using, Ne, Ar and Kr as assisting atoms [15]. Conventional model for implantation do not predict the appearance of this peak. This effect is probably related to a competitive process involving sputtering and implantation. As the energy of the assisting Xe ions increases the implantation of Xe also increases. However, as the energy increases further the sputtering phenomenon start to be more significant. In this range of energy the sputtering process followed by the implantation of the xenon atoms is less effective, thus reducing the concentration of Xe into the matrix. The result is the appearance of a maximum at certain energy.

5. Conclusion

Amorphous silicon was deposited by ion beam assisted deposition, IBAD, using xenon noble gas for sputtering a silicon target and simultaneously bombards the film. It was observed that the bombardment reduces drastically the deposition rate, but works as a powerful technique for implanting relatively high concentration of noble gases into the amorphous silicon network at incredible low energy as compared with conventional implantation technique. The incorporation of xenon increases substantially the density of the films. The stress of all films was compressive, and was attributed to the incorporation of xenon atoms inside small voids.

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References