Fig. 1 shows the hardness variation of the pristine and irradiated $Fe_3O_4$ films with depth from 0 to 1 500 nm. For the pristine film, the hardness declines from the maximum value of 34 GPa to a steady value of 3.9 GPa, indicating an indentation size effect. After irradiation, the films' hardness value increases slightly, but is not monotonic varying. In another words, the hardening and softening phenomena do exist for $Fe_3O_4$ material induced by SHI irradiation. Fig. 2 shows the dependence of nano-hardness on the Kr-ion fluence for $Fe_3O_4$ films. It is obviously, at low fluence level, as the formation of defects in the $Fe_3O_4$ films induced by SHI irradiation, the value of nano-hardness increases slightly; and when the fluence increases from $5.0 \times 10^{11}$ to $1.0 \times 10^{12}$ ions/cm$^2$, the value increases dramatically as the defects accumulation; after irradiation of $1.0\times10^{12}$ Kr-ions/cm$^2$, the value of nano hardness reaches to the maximum of 5.2 GPa, which is mainly because the number of grain boundaries increases significantly and acts as pinning sites of grain boundaries; when the irradiation fluences exceeds a certain value ($1.0\times10^{12}$ Kr-ions/cm$^2$ for our work), the nano-hardness decreases consistently, which also can be explain that the annealing effect (relaxation) reduces the density and the size of vacancies, as a result of the numerous combinations of interstitials and vacancies. Though we can not confirm the type and distribution of the vacancy-type defects by our experiments, the changing regularities of magnetic and micro-mechanical properties of irradiated $Fe_3O_4$ films shows excruciating uniform with different fluences, and they are significant correlation. In fact, the further measurement such as positron annihilation spectroscopy is carried out.

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# 3 - 10 Swift Heavy Ion Induced Modification of Fe/Cu Multilayers

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When swift heavy ion (SHI) passes through metallic multilayers, the kinetic energy of the ion is mainly deposited to target electron subsystem (electronic energy loss, Se) by the inelastic collisions involving excitation and ionization of the target atoms, which could induce atomic displacements and modify the interfacial structure [1−6]. Therefore, through the study of the process of the interfacial atoms diffusion induced by SHI irradiation, we could explore the possible mechanism of atomic displacement induced by swift heavy ion irradiation.

Multilayers with structure of Si/[Fe(10 nm)/Cu(10 nm)]$_5$ (the subscript refers to layer number) were prepared by alternating depositions of pure iron (99.99% Fe) and copper (99.99% Cu) on cleaved Si(100) substrates by magnetron sputtering at room temperature (RT). Before irradiation experiments, the samples annealed at 300 degrees Celsius for 2 h. Then, the multilayers were irradiated at RT with 792 MeV Ar to $1\times10^{12}$, $1\times10^{13}$ and $3.4\times10^{14}$ ions/cm$^2$. These samples were characterized using depth profile analysis of Auger electron spectroscopy (AES) and transmission electron microscopy (TEM) respectively. Then the intermixing among the different layers of the samples induced by incident heavy ions were investigated systematically.

AES depth profiles of the as-deposited Si/[Fe(10 nm)/Cu(10 nm)]$_5$ multilayers, along with the samples irradiated at RT with 792 MeV Ar-ion, are shown in Fig. 1. The abscissa and the ordinate represent the sputter time and the Si, Fe, and Cu atomic concentrations (at.%), respectively. The interfaces of as-deposited multilayers were found not to be sharp, and rather wide interfacial region could be observed, whereas the layered structure also could be observed. After irradiation at $1.0\times10^{12}$ and $1.0\times10^{13}$ ions/cm$^2$, for the Fe layer, the Fe concentration was higher and the Cu concentration was lower than those of the corresponding part of as-deposited samples; for the Cu layer, the Fe concentration was lower compared with that of the as-deposited samples, and the Cu concentration was higher, which indicates that a de-mixing between the Fe and the Cu layers occurs. But when the irradiation fluence was $3.4\times10^{14}$ ions/cm$^2$, the layered structure completely disappeared.

TEM images of Si/[Fe(10 nm)/Cu(10 nm)]$_5$ irradiated at room temperature by 792 MeV Ar-ion are shown in Fig. 2. For the as-deposited multilayers, the layered structure of the multilayers was not obvious. After irradiation at $1.0\times10^{12}$ and $1.0\times10^{13}$ ions/cm$^2$, the layered structure could be observed. Up to a fulence of $3.4\times10^{14}$ ions/cm$^2$, the layered structure completely disappeared.

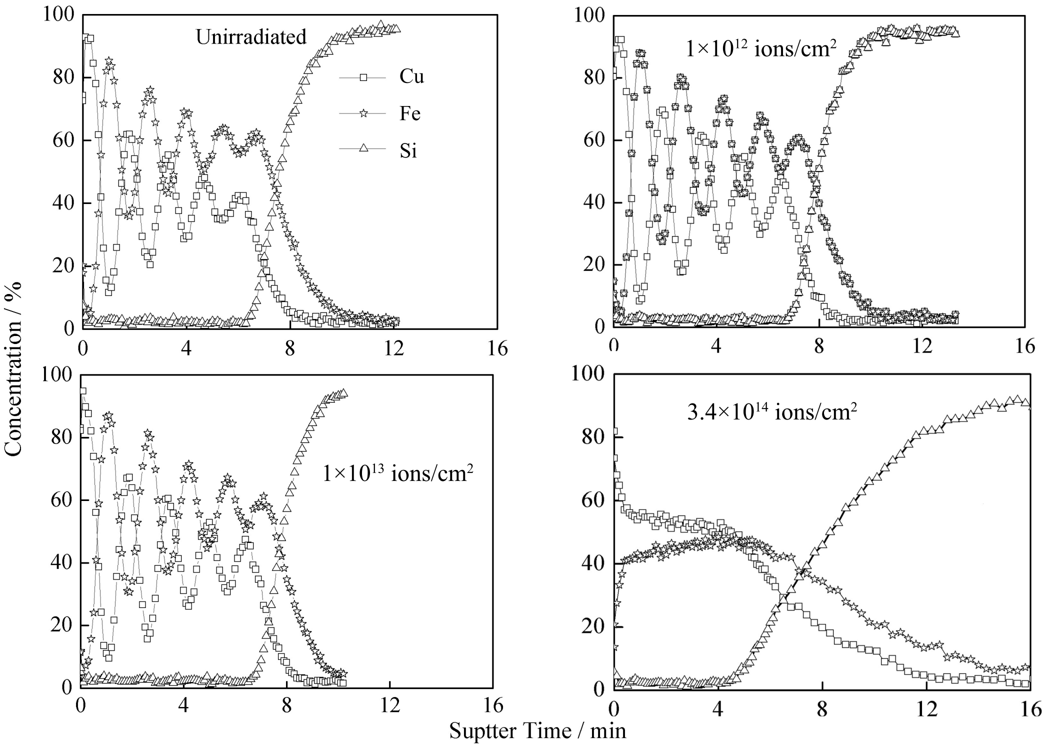


Fig. 1 AES depth profiles of Si/[Fe(10 nm)/Cu(10 nm)]$_5$ irradiated at room temperature by 792 MeV Ar-ion.

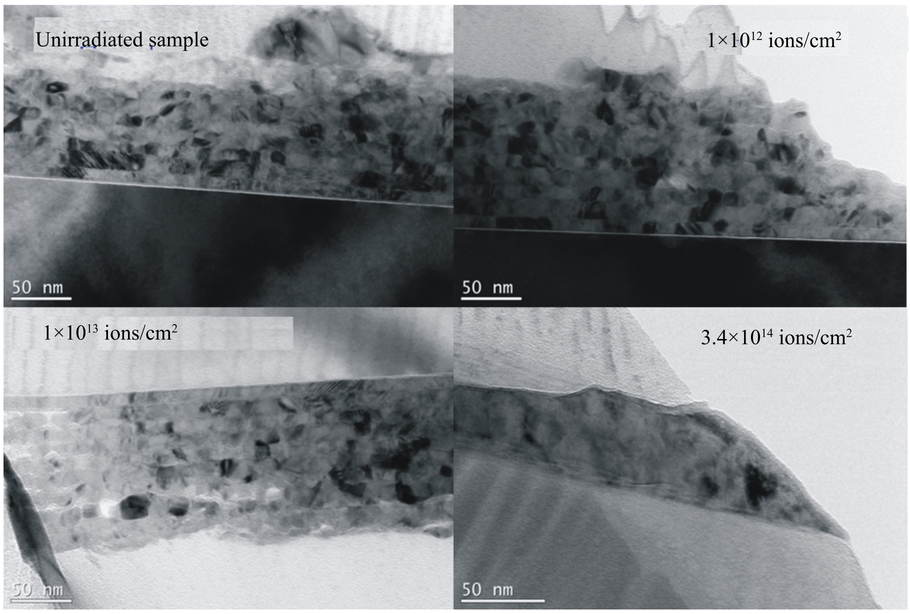


Fig. 2 TEM images of Si/[Fe(10 nm)/Cu(10 nm)]$_5$ irradiated at room temperature by 792 MeV Ar-ion.

The results showed that when the fluence reached $1.0\times10^{12}$ and $1.0\times10^{13}$ ions/cm$^2$, the demixing of interfaces were observed. While for higher fluence of $3.4\times10^{14}$ ions/cm$^2$, the inter-mixing between Fe and Cu layers was observed.

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