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Resistance changes in thin metallic films under ion bombardment

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Abstract. Resistance changes in thin films of copper, aluminium and bismuth have been studied under the bombardment of nitrogen, carbon and argon ions. Variations in resistance with implantation dose have been observed upto doses of $\sim 3 \times 10^{17}$ ions/cm^2 for ion energies in the range 40 to 120 keV. The results are discussed in terms of desorption of gases from the film and a composite action of sputter removal of the film and its structural changes upon ion bombardment. A simple theoretical model is discussed which can qualitatively explain the experimental observations.

Keywords. Ion bombardment; thin films; sheet-resistance; sputtering; implantation dose.

1. Introduction

Considerable work is now in progress to study the changes in conduction processes in thin film resistors after ion implantation. Deery *et al* (1973) studied tantalum films under reactive (N_2^+, O_2^+) and non-reactive (Ar^+) ion bombardment and observed that in the former case after an initial decrease, there is an increase in the resistance of film with dose, upto doses of $\sim 8 \times 10^{16}$ ions/cm^2. The resistance invariably shows a decrease with further increase in dose and finally a rapid increase. They attributed the initial decrease to desorption of gases, the latter increase to damage and sputtering effects, the subsequent decrease to formation of compound phases and the final increase to rapid sputtering. The interesting feature of the intermediate decrease, however, could not be confirmed until Wilson *et al* (1976) reported electron microscope observations on an equivalent system. These results indicate that for intermediate doses, there are transformations of chemical phases in the bombarded tantalum films, which are also associated with corresponding sudden changes in the temperature coefficient of resistance of the films.

Later Belson and Wilson (1978) developed a simple theoretical model for the variation of sheet resistivity of metallic films with the ion implantation dose and showed that the resistance-dose curves could be explained without consideration of the sudden chemical changes. They explained the curves in terms of the composite action of sputtering and variation in total ion content of the film. The model, however, does not consider the microscopic changes taking place in the film and hence, may be considered to be at a preliminary stage.

The above studies demonstrate a need for more experimental work for a full understanding of the different processes involved. Experimental studies of ion implanted thin films were therefore undertaken to study different film ion combinations. Since

chemical as well as sputtering effects are different for different film ion combinations, this data can be used to characterise the two effects separately. In the present paper we report the results on N_2^+, C^+ and Ar^+ bombarded Cu, Al and Bi films. A theoretical model has also been presented to explain the experimental results.

2. Ion implantation set up

The implantations in the present experiments were carried out using the 200 keV ion implantation system completely designed and fabricated in this laboratory. The central column of the system consists of an ion source, electrostatic focusing lens, magnetic mass analyser, accelerating column, beam sweeping system and the implantation chamber. The ion source is of diffused discharge type, in which plasma is produced by bombardment of electrons emitted by a hot tungsten filament on the gas molecules. With discharge currents of ~200-500 mA and the extractor voltage of ~5-10 kV, stable ion current upto 6 mA can be easily obtained from the ion source. To control the divergence of outcoming ion beam, a three-electrode acceleration-deceleration type electrostatic lens immediately follow the ion source. The ion beam is then magnetically analysed by a 60° single focusing sector magnet of 50 cm radius. The selected beam is passed through a ten-stage accelerating column, the potential drop across which is given by a 200 kV, 10 mA doubler type of high voltage generator. The accelerated beam is focussed on the target at a size of 3×8 mm^2 and for implantation over wider areas, an electrostatic beam sweeping system is used. The implantation chamber can hold four substrates in a single operation. The substrate orientation and temperature can be externally controlled. The ion current upto ten microamperes can be obtained at the substrate.

3. Experimental

The metallic thin films used in the experiments were deposited in an 8 inch bell jar coupled to a diffusion-rotary type of a vacuum system, through liquid nitrogen trap. The deposition system has nine electrical feed-throughs used for filament heating, substrate annealing and measurement of resistivity of the deposited film. The evaporation was carried out in a background vacuum of $\sim 10^{-6}$ Torr. A low evaporation rate was used to obtain uniform deposits. The thicknesses of films were determined using Tolanski's method as well as by weight measurements. These methods together can give a thickness accuracy of 5–10%. Each film had dimensions of $1 \times 0{\cdot}5$ cm^2 with thickness varying from 300 to 800 Å. Silver pads were deposited as electrical contacts on either side of the film along the length. During ion implantation, the contact pads were appropriately masked. Ions were implanted on the films at beam currents of 5 μA. After every implantation cycle, a period of 3–5 min was provided for the cooling of the substrate before the resistance was measured *in situ*, using a universal bridge at a frequency 1 kHz.

4. Results

Figure 1 shows the variation in the resistance of Cu film (thickness 600–800 Å) as a function of N_2^+ and C^+ ion doses for different energies. R_I represents the initial value

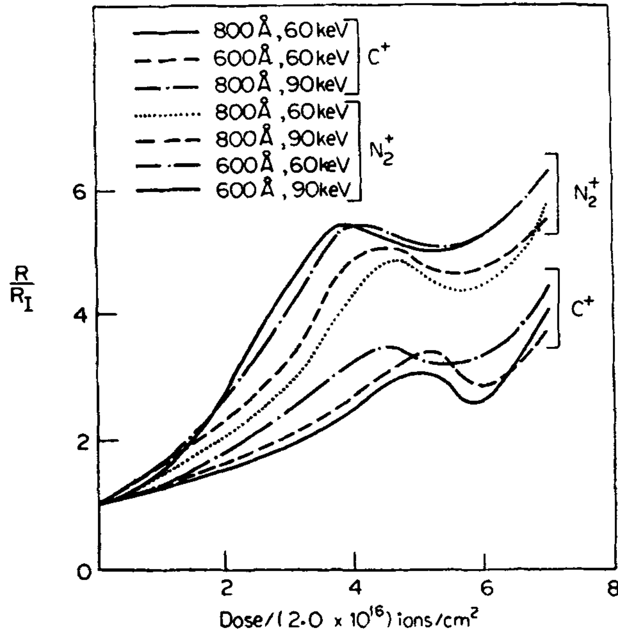

Figure 1. Resistance dose curves for C^+ and N_2^+ bombarded copper films.

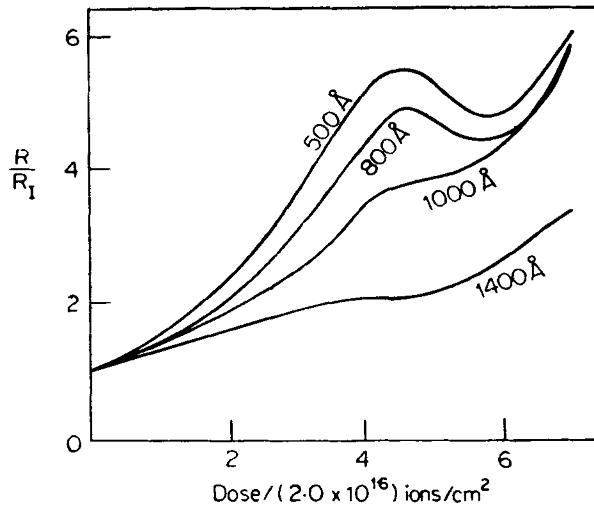

Figure 2. Resistance dose curves for N_2^+ bombarded copper films (60 KeV ion energy).

of the resistance of the film. The curves exhibit a change in their tendency to increase at doses of $\sim 8 \times 10^{16}$ ions/cm^2. With increase in energy, increase in the resistance is more rapid and the peak position shifts to lower dose values. The peak becomes less pronounced with increase of implantation energy. Figure 2 shows the variation of resistance with the film thickness, keeping other parameters same as in figure 1.

Figures 3 and 4 show results on aluminium and bismuth films, implanted with N_2^+ and C^+ ions. Though the values for change in resistance and peak dose are

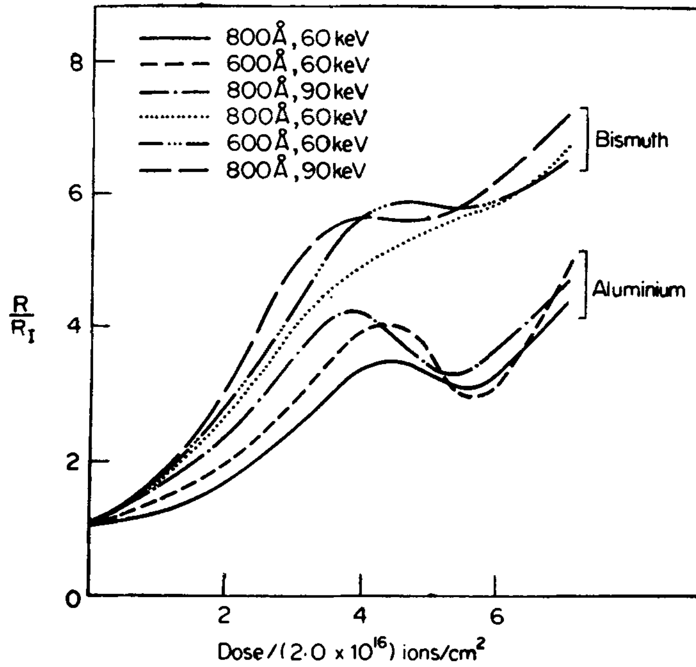

Figure 3. Resistance dose curves for N_2^+ bombarded aluminium and bismuth films..

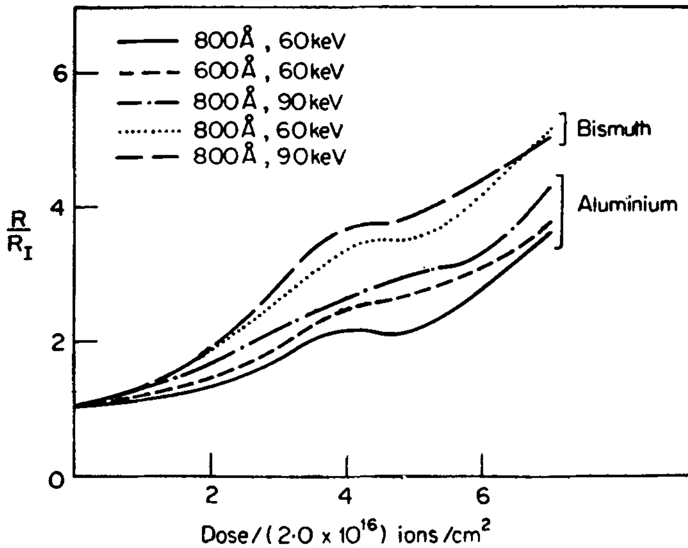

Figure 4. Resistance dose curves for C^+ bombarded aluminium and bismuth films.

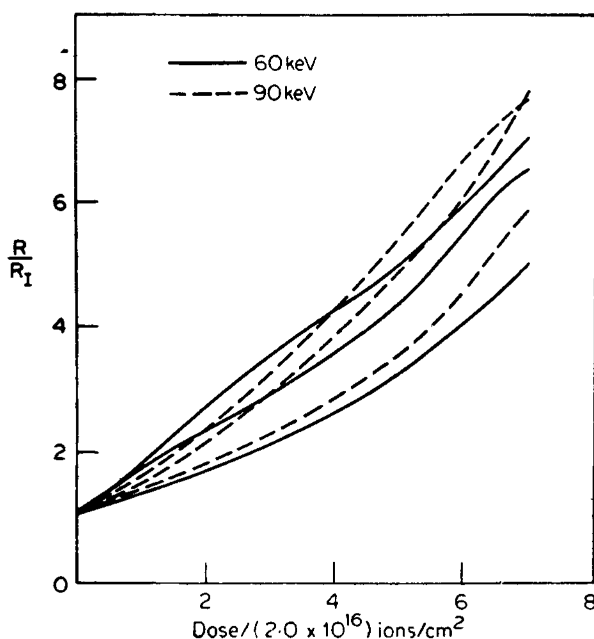

Figure 5. Resistance dose curves for A^+ bombarded aluminium, copper, and bismuth films.

different in these cases, the characteristics are similar to those obtained in the case of copper (see figure 1).

In figure 5 the change in resistance for the 800 Å thick films of Cu, Al and Bi has been shown under argon bombardment, for three different energies. There is an absence of the peak at intermediate dose observed under reactive bombardment. It may be noted that the change in resistance at low doses is faster at higher energy in all these cases.

At low doses it was observed that the resistance drops by 4 to 7% before it starts increasing. On the dose scale used in the figures, however, this effect cannot be clearly seen.

5. Discussion

Though our results are consistent with those reported earlier on tantalum films (Deery *et al* 1973; Wilson *et al* 1976; Stephens and Wilson 1978) the characteristic peaks in our results are much less pronounced. The increase in resistance in our case, however, is fairly linear until at dose of $\sim 7 \times 10^{16}$ ions/cm^2. The rise in resistance of copper film is generally found to be more compared to aluminium film under similar conditions of ion implantation. This can be attributed to the higher (approximately double) value of sputtering coefficient of copper as compared with aluminium. Also the resistance peaks in copper appear to be less prominent than in aluminium. At low doses the nature of the curves is similar in both the cases. If the rise in resistance is due to a composite action of damage and sputtering, signifi-

cant changes in the curves would result only at a higher dose, when sputtering starts dominating. In §6 we discuss a theoretical model, which qualitatively explains these findings.

In bismuth films, we observe that the percentage rise in resistance is of the same order as in copper. In view of the different sputtering rates of these two materials, we can attribute the results to the difference in damage-resistance relationship. Since the carrier transport processes in bismuth films are complex, it is very difficult to interpret results in simple terms.

Implantation carried out with argon ions differs from that of carbon and nitrogen ions mainly in two respects, (i) sputtering coefficients for argon is more and (ii) the argon ions are non-reactive. The results on copper, aluminium and bismuth films implanted with argon ions show a continuous rise in resistance with dose and the peak at the intermediate dose is absent in each case. This shows that unless a definite theoretical framework is developed it is difficult to say, whether the peaks observed in N_2^+ and C^+ bombardments are due to reactions taking place in the films, or due to their low sputtering rate. There is some experimental evidence for the first cause, while in the theoretical model proposed by Belson and Wilson (1978), the peak in the resistance dose curve is accounted for without considering chemical reactions.

We have also carried out experiments on ion implanted films, annealed in the temperature range of 400° C and 600° C for different periods and the pilot readings indicate significant variations from the results on the 'as-deposited' films. These results, to be published separately, are expected to throw more light on the processes taking place in ion implanted films.

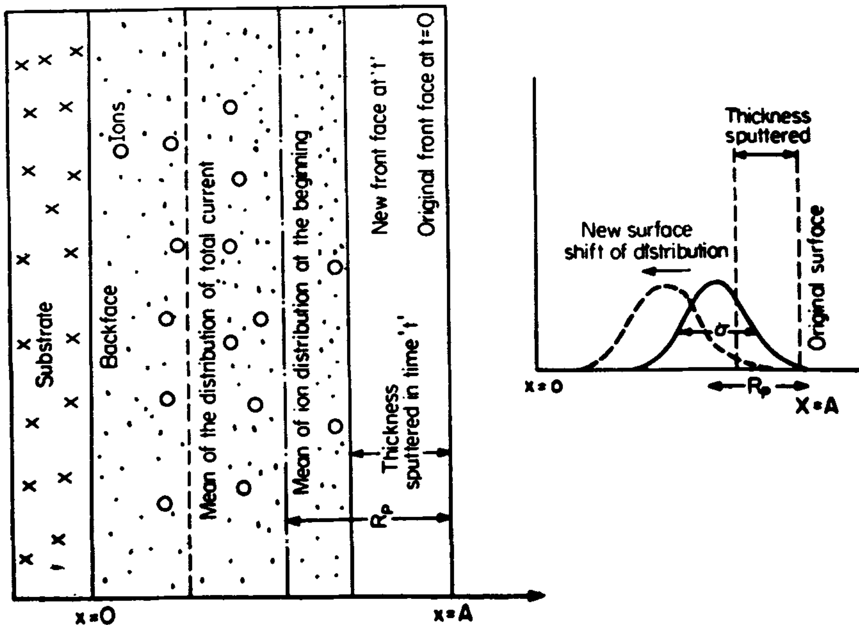

Figure 6. Reference system used in the theoretical model.

6. Theoretical models

In the theoretical model proposed by Belson *et al* (1978) the nature of the resistance-dose curves of the ion-implanted metallic thin films is accounted for is terms of sputtering process which results in (i) reduction in film thickness and (ii) variation in total ion content of the film. The first effect can only lead to increase in the film resistance whereas the second can lead to a decrease after a substantial amount of film material is removed. It may be pointed out that at low doses, the result of both these effects is to increase resistance of the film. [At this dose level the gas desorption is almost complete]. The interplay of the two effects referred to above can explain the curves obtained experimentally only if appropriate weight is associated with each effect. This model, however, lacks in accounting for the dependence of the film resistance on the variation in ion concentration as a function of depth and also the size effect corresponding to the rapid thinning of the film. We have tried to develop a simple model incorporating the above mentioned features to explain the experimental results.

Consider a metallic film of thickness A, on an insulating substrate as shown in figure 6. Choosing the origin of co-ordinate system at the surface of the substrate and assuming the ion profiles to be Gaussian (Belson and Wilson 1978) the expression for the number of ions (scattering centres) stopping between x and $x+dx$ in time t and $t+dt$ is given by

$$dN = \frac{N\,dx}{(2\pi\,\sigma^2)^{1/2}} \exp\left[-\left\{\frac{x-\left(A-\frac{N\,st}{\rho}-R_p\right)}{\sqrt{2}\,\sigma}\right\}^2\right] dt, \tag{1}$$

where N is the number of ions incident per second per unit area, S the sputtering coefficient, ρ the number density of atoms in the film, R_p is the projected range of ions and σ is the half-width of ion distribution. In this equation both the effects *viz.* the thinning of the film due to sputtering and the corresponding shift in ion distribution have been accounted. The formula explicitly shows the contributions of physical parameters such as ρ, S, R_p and σ. Further, considering the film to be a stack of many thin sheets, each having a thickness of dx, the expression for the resistance R of the thin film (1×1 cm^2 in area) can be written as

$$R\,(\text{dose}) = \frac{1}{\displaystyle\int_0^{A'(t)} \frac{dx}{\rho_b(x)}} \tag{2}$$

Here ρ_b is the specific resistivity of the layer between x and $x+dx$, and A' denotes the residual thickness of the film at a certain stage of implantation. In equation (2) the decrease in the upper limit on the integral accounts for the increase in the resistance because of the sputter removal of the film. The value of $\rho_b(x)$ depends on the local structure of the film between x and $x+dx$ and therefore changes the resistance of the film in accordance with the nature of damage due to implantation. As a first approximation, we consider $\rho_b(x)$ to be proportional to the number of scattering centres dN in the layer between x and dx, thus,

$$\rho_b(x) = \alpha\,dN. \tag{3}$$

The parameter α cannot however be a constant. This is because, as implantation proceeds, the 'as deposited' high resistivity film undergoes structural relaxation and it gets transformed into a structurally ordered low resistivity film. (Note that a disordered thin film has a very high resistivity than the corresponding ordered film, obtained by annealing of the disordered film.) On the basis of this criterion we allow a decrease in α at a rate proportional to the rate of energy deposition in the layer between x and $x+dx$. This effect is perfectly local and it has nothing to do with the annealing due to average temperature rise of the film. The contribution of the latter effect is extremely small at beam currents of a few $\mu A/cm^2$, employed in the present case. In addition to the above aspects we have also taken into account the size effect on resistivity of thin film, when it is thinned below a thickness of ~ 200 Å. The results of our calculations are given in figures 7 and 8. Figure 7 shows the variation in

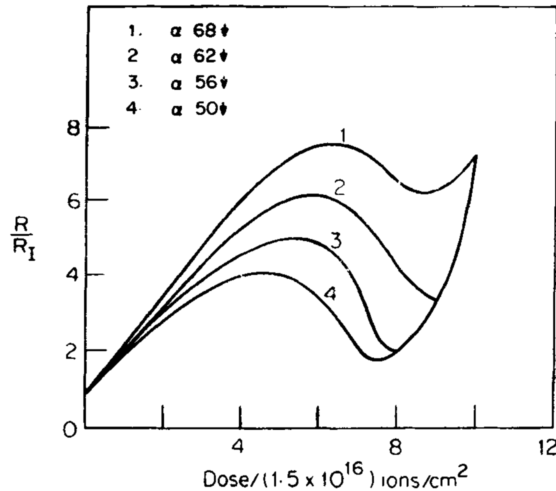

Figure 7. Resistance dose model curves for film thickness 500 Å, sputtering coefficient=0·6, projected range $R_p=357$ Å, half-width of distributions $\sigma=250$ Å.

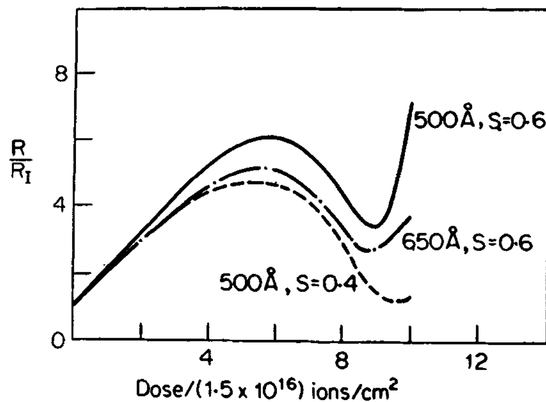

Figure 8. Resistance dose model curves for $R_p=357$ Å, $\sigma=250$ Å and $\alpha=62\downarrow$

nature of the resistance with dose for various values of α. It can be seen that the variation in the nature of the curves is similar to the one experimentally observed. Figure 8 shows the dependence of the resistance dose curve on the sputtering coefficient S and film thickness A. A decrease in S or an increase in A is seen to decrease the resistance change.

7. Conclusions

The resistance variations with implantation dose have been studied for various film-ion combinations and the results have been found to be similar to those of the experiments on tantalum films reported earlier. A simple theoretical model has been proposed to explain the observations. The model can be improved by using first principle calculations on the resistivity changes in structurally transformed film layers, which would give a physical basis to the values of parameters used in the results reported here. Also, more experiments on similar lines have to be performed for a full understanding on the processes involved and this work is now in progress.

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