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Laser-induced damage formation and tungsten deposition on GaAs

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Laser-induced damage formation and deposition of tungsten from WF_6 on GaAs using a focused CW scanning argon-ion laser beam are both investigated. Laser-induced damage produced at power levels lower than 150 mW results in bumps as high as 100 nm. Their chemical composition, analyzed by AES, shows no arsenic loss, suggesting that they are not induced by thermal decomposition of GaAs. Deposition of W is found to occur in a narrow process window ranging from 57 to 75 mW. AES depth profiles show significant incorporation of As in the deposited film, even though the temperature of the GaAs surface during deposition is estimated to be less than 400°C.

1. Introduction

Tungsten is known to form a good Schottky contact on GaAs [1,2]. The interest in laser direct writing of conductive materials such as W for VLSI applications has increased in recent years [3–5]. Laser-induced chemical vapor deposition using an Ar^+ laser is a pyrolytic process, using the focused beam as the heat source. Recently, laser-induced deposition of tungsten on Si by silane reduction at low temperature has been reported [6]. This particular pyrolytic process could be used on thermal sensitive substrates such as GaAs. For tungsten deposition, $W(CO)_6$ has been used in the past as the precursor, but its low vapor pressure limits the deposition rates [9] which is not the case for WF_6. Here we report a preliminary study of W deposition on GaAs using WF_6. Since the formation of morphological damage on GaAs was mainly studied for pulsed lasers [7,8], it was found necessary to first perform a study of damage formation induced by a scanning CW Ar^+ laser beam. We suggest that laser-induced damage formation is due to enhanced atomic diffusion caused by electronic excitation.

2. Experiment

The laser direct writing system is composed of a CW argon-ion laser focused on the substrate using a long working distance microscope objective with a numerical aperture of 0.15. The maximum power available at the substrate on the 514.5 nm operating line is 1.3 W. The spot diameter at e^{-2} of maximum intensity, measured by the scanning knife-edge technique, is 3.7 μm. The substrate is placed in a 10 cm^3 stainless-steel reaction chamber pumped down to a base pressure of $\sim 10^{-2}$ Torr by a mechanical pump. The chamber window is made of fused silica. The reaction chamber is mounted on computer-controlled X–Y translation stages, having a spatial resolution of 0.1 μm and a maximum velocity of 100 μm/s. Substrates used are (100) semi-insulating liquid-encapsulated Czochralski GaAs. In preparation for experiments, samples were degreased in hot TCE, acetone, propanol and rinsed in de-ionized water. Then they were cleaned in hot HCl : H_2O (1 : 1), rinsed in de-ionized water and dried in flowing nitrogen. Deposition temperature of the substrate is 30°C.

3. Damage formation

In this work, a damage is defined as a morphological modification of the GaAs surface that is visible under white light using a 80 × magnification. The damage threshold power P_{th} is defined as the minimum power at which such damage is formed. Fig. 1 shows a scanning electron microscopy (SEM) photograph of typical damage produced in vacuum ($\sim 10^{-2}$ Torr) using a velocity of 10 μm/s and a laser power of 100 mW. At low power levels, the damaged regions are rough, with bumps as high as 100 nm as measured by a contact profiler (Sloan Dektak 3030), while at high power levels ($P > 300$ mW), damaged areas are smooth and in the form of trenches, suggesting a melting of the substrate.

Fig. 2 shows Auger depth profiles obtained on (a) a line of damage produced at 10 μm/s using a power of 100 mW and (b) the unilluminated substrate. The fact that no arsenic loss is observed in the damaged region suggests that the damage is produced below 650°C, the temperature at which thermal decomposition of GaAs is believed to occur [10].

Fig. 3 shows that P_{th} increases with scan velocity v. From the three-dimensional steady-state calculation of Nissim et al. [11], where the temperature dependence of the thermal conductivity has been taken into consideration, we evaluate the temperature rise of the GaAs surface caused by the laser irradiation to be ~ 350°C for 65 mW and ~ 625°C for 100 mW. Note that this temperature range is below the onset temperature for

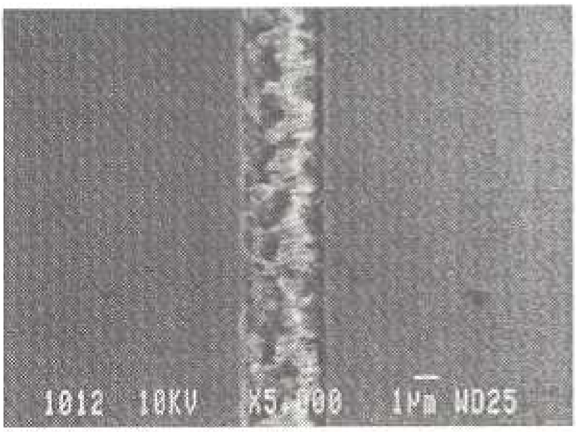

Fig. 1. SEM photograph of laser damage on GaAs.

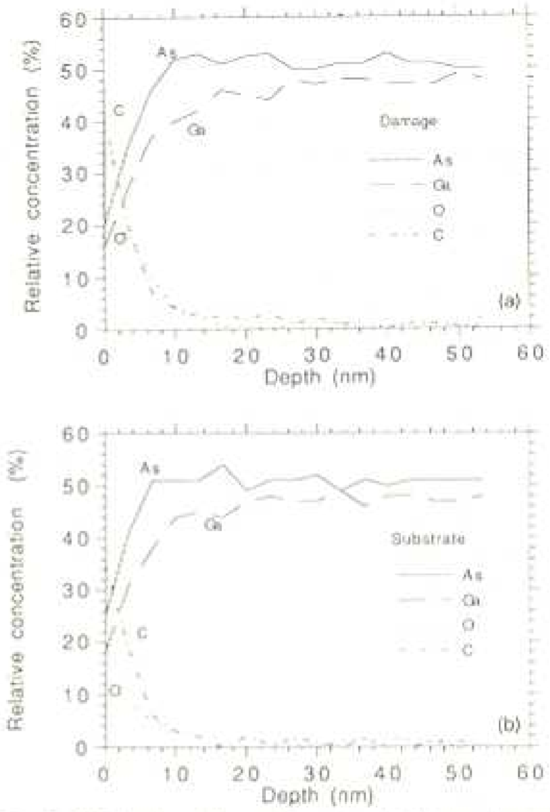

Fig. 2. AES depth profiles performed on (a) a laser damaged region and (b) the unilluminated substrate.

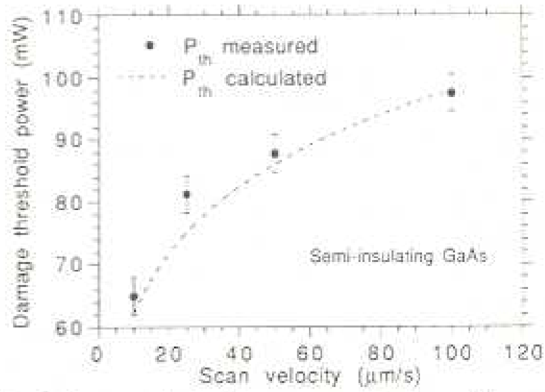

Fig. 3. Damage threshold power as a function of the scan velocity. The dashed line represents damage threshold powers calculated using the simple model proposed in the text.

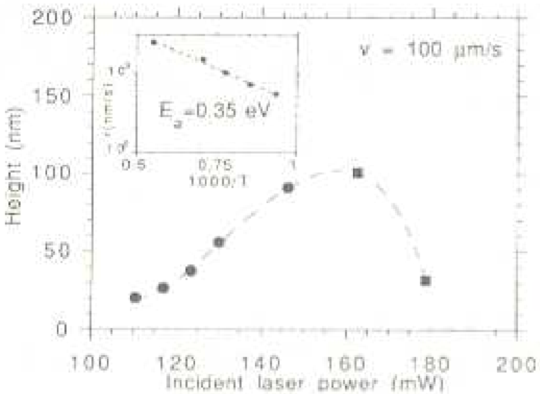

Fig. 4. Laser-induced damage height as a function of the incident laser power. The inset shows an Arrhenius plot of damage "growth rate".

thermal decomposition, 650°C. This is consistent with the constant As concentration discussed above. For a surface heat source of dimensions w_0, a quasi-steady-state temperature distribution is set up on the time scale $\tau_0 = w_0^2/4D_t$ [12], where D_t is the thermal diffusivity of the substrate. For GaAs and $w_0(e^{-2}) = 3.7$ µm, we find that $\tau_0 \approx 0.3$ µs. Since the minimum dwell time used is 37 ms, which is much greater than τ_0, the substrate reaches thermal equilibrium rapidly and the temperature rise should not depend upon scan velocity. The dashed line of fig. 3 will be discussed below.

Fig. 4 shows the height of the bumps produced as a function of the laser power for damage produced under vacuum. The maximum of the curve corresponds to a temperature rise of the GaAs surface to near the fusion temperature of 1238°C [13], suggesting that the decrease as the power increases beyond this is due an evaporation of material upon melting.

Since thermal decomposition of GaAs cannot explain the formation of bumps, we suggest that this phenomenon is due to atomic diffusion from the bulk to the surface. A simple calculation shows that this process requires diffusion coefficients as large as 10^{-10} cm^2/s, considerably higher than the values of 10^{-14} and 10^{-17} cm^2/s reported for As and Ga, respectively, at 850°C [14]. Thus, a simple atomic diffusion cannot explain the process. We propose that the high density of incident photons creates a dense electron–hole plasma which may weaken bonds inducing defect formation [15–17]. For instance, Welsh et al. suggested that residual stresses induced during laser heating could produce defects [18]. The damage could result from sizable atomic diffusion in a material containing a large concentration of defects. Since atomic diffusion is a thermally activated process, the bump shape and height could be explained by the temperature profile until melting is reached for $P > 160$ mW. Plotting the "growth rate" r for the first five points of fig. 4 on an Arrhenius plot, an activation energy of $E_a = 0.35$ eV is obtained. While the bump formation mechanism is unclear, it is interesting to note that this E_a is close to the 0.33 eV activation energy value reported for As surface diffusion on (100) GaAs [19]. We propose that the product r by τ (where τ is the dwell time) is constant at threshold damage power. Using this, it is possible to calculate the theoretical damage threshold power for different scan velocities. As shown in fig. 3, a good agreement is found between the calculated values and the experimental ones, suggesting the validity of the simple proposed model.

4. Tungsten deposition

A preliminary study of laser direct writing of tungsten on GaAs has been performed. Lines have been made at a scan velocity of 25 µm/s with power of 57 to 75 mW, using different mixtures of $WF_6:H_2$ and $WF_6:SiH_4$. Depositions have also been produced without using any reducing gas, suggesting that GaAs plays a role in the deposition mechanism. Fig. 5 shows a SEM photograph of a typical line made using a scan velocity of 25 µm/s and a gas mixture of 1 Torr SiH_4 and 10 Torr WF_6. Depositions are found to occur in a narrow process window, of the order of 10 mW, and difficult to reproduce. Line thicknesses are usually less than 70 nm. At power levels higher than 80 mW, etching of GaAs is observed. AES depth profiles made on deposited lines show significant incorporation of arsenic in the film, even though the temperature of the GaAs surface

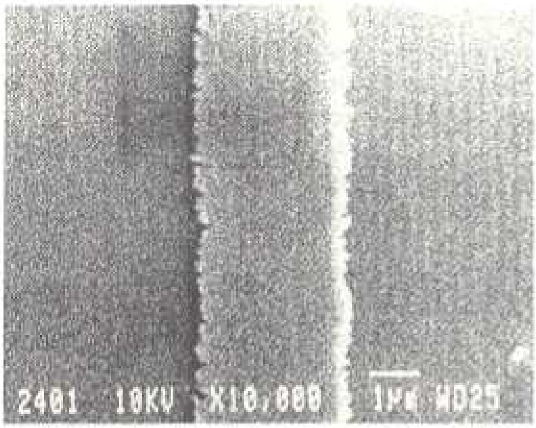

Fig. 5. SEM photograph of a tungsten line deposited on GaAs by laser-CVD using a mixture of $WF_6:SiH_4$ (10:1) and $v = 25$ μm/s.

during deposition is estimated to be less than 400°C. This study continues and further results will be published elsewhere.

5. Conclusion

Ar^+ laser damaged regions on GaAs are bumps and show no arsenic loss. It is suggested that enhanced atomic diffusion, due to defect formation from electronic excitation, produces the observed damages. A simple model has been proposed to predict damage threshold powers as a function of scan velocity. Preliminary results on laser direct writing of W from WF_6 show a narrow process window and considerable As incorporation in the film.

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