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Ion-beam-induced Intermixing of $WSi_{0.45}$ and GaAs

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Abstract

The systematics of ion-beam-induced intermixing of $WSi_{0.45}$ on GaAs has been studied after through-implantation of silicon or oxygen in the dose range 10^{13}–5×10^{16} cm^{-2}. Secondary ion mass spectrometry profiling shows significant knock-on of silicon and tungsten into the GaAs at the high dose range in accordance with Monte Carlo simulations, but there is virtually no electrical activation (less than or equal to 0.1%) of this silicon after normal implant annealing (900 °C, 10 s). This appears to be a result of the high level of disorder near the metal–semiconductor interface, which is not repaired by annealing. This damage consists primarily of dislocation loops extending a few hundred angstroms below the end of range of the implanted ions. Extrapolation of the ion doses used in this work to the usual doses used in GaAs device fabrication would imply that ion-induced intermixing of WSi_x will not be significant in through-implantation processes.

1. Introduction

One of the biggest problems in GaAs technology is the metallization, both for Schottky and ohmic contacts. In most cases alloyed ohmic contacts are still used—this implies a melting and flowing of the eutectic, limiting downscaling of the contacts, as well as spiking into the GaAs. The metal contacts commonly used in device applications generally exhibit a rather restricted range of Schottky barrier heights, around 0.7–0.8 eV. Recently the use of a thin (15–30 Å) silicon interface layer between the GaAs and a metal overlayer has been demonstrated to yield contacts with a 1 eV Schottky barrier height [1]. The most common gate metallization for GaAs field effect transistors (FETs) is WSi_x, which is well established in the self-aligned refractory gate technology. In this case the refractory gate acts as a mask for subsequent n^+ implantation which reduces the resistance between the FET channel and the source and drain [2–5]. The implant must be activated by a high temperature annealing step (850–900 °C), and therefore the stability of the WSi_x–GaAs interface has attracted much attention [6–8].

One issue which has not received as much interest is the effect of ion-beam-induced intermixing of the WSi_x and the GaAs during through-implantation of the WSi_x with either silicon (for doping of the GaAs) or oxygen (for isolation purposes). A further example in which through-implantation might be used is the use of acceptor implants to create a thin p^+ layer immediately under the Schottky contact in order to enhance the barrier height [9–12]. The effect of knock-on of tungsten and silicon in the GaAs substrate is potentially very important—tungsten is a deep acceptor and would be expected to compensate the donors in n-type material, whereas silicon is amphoteric but is generally a donor. The latter could lead to uncontrolled doping characteristics in the GaAs after high temperature annealing.

In this paper we explore the stability of $WSi_{0.45}$ layers on GaAs to high doses of silicon or oxygen

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ions, and the effect of subsequent thermal annealing on interdiffusion characteristics at the metal–semiconductor interface. We also explore the use of $WSi_{0.45}$ as an overlayer for through-implantation of low doses of silicon in order to form n-type regions for FET channels.

2. Experimental

Deposition of the $WSi_{0.45}$ films was performed in a standard S-gun sputtering system. The sputtering sequence was fairly standard for this type of deposition—initially the GaAs substrates were sputter cleaned for a few minutes in a relatively high pressure (low energy) argon beam. The film deposition was also carried out in argon using separate tungsten and silicon sources. Thicknesses between 300 and 1000 Å were examined. The choice of sputtering conditions and film stoichiometry was based on previous calibration experiments which determined the optimum film properties for our particular applications for Schottky contacts [13]. The GaAs substrates were undoped, (100), semi-insulating samples grown by the liquid-encapsulated Czochralski technique. They were etched for 5 min in 5:1:1 H_2SO_4:H_2O_2:H_2O prior to loading into the sputtering system. The WSi_x–GaAs samples were implanted with oxygen or silicon ions at doses between 5×10^{15} and 5×10^{16} cm^{-2} for study of intermixing effects upon through-implantation or at doses of 10^{13}–5×10^{13} cm^{-2} for study of the formation of n-type layers for FET channel formation. The energies of these implants were chosen either to remain mostly in the WSi_x or to penetrate approximately 0.2 μm into the GaAs, depending on the specific experiment. Annealing was carried out in a Heatpulse 410 system at 900–950 °C for 10–300 s using the proximity technique. The near-interface region in the samples was examined before and after annealing by ion channelling, secondary ion mass spectrometry (SIMS) and cross-sectional transmission electron microscopy (TEM). In some cases the WSi_x was removed by NF_3 reactive ion etching, and capacitance–voltage (C–V) measurements were made in the GaAs using a mercury probe as a contact.

3. Result and discussion

Our initial task was to determine the uniformity of WSi_x thickness deposited on a wafer 2 inches in diameter. To avoid the possible problem of interaction of the WSi_x with the GaAs substrate, we did this on a silicon wafer. From ion-channelling measurements across a wafer diameter, the thickness uniformity was less than or equal to 10% (approximately 1000 ± 100 Å) for our sputtering conditions. A Monte Carlo simulation using the Transport of Ions in Matter (TRIM) program showed that each 100 Å of WSi_x requires approximately 10 keV of energy for silicon ions to penetrate. Therefore variations in WSi_x layer thickness of order 100 Å over a wafer 2 inches in diameter should lead to significant spatial variations in the total dose and resulting charge distribution in any n-type channel region formed by through-implantation of silicon. We estimate that for through-implantation of silicon through 500 Å of $WSi_{0.45}$, the thickness uniformity must be better than 3% over the whole wafer area in order to achieve acceptable metal semiconductor field effect transistor (MESFET) threshold voltage uniformity.

We also deposited $WSi_{0.45}$ on GaAs samples and annealed them at 950 °C for 60 s. Ion channelling showed a very slight amount of diffusion of tungsten, confined to within 300 Å of the metal–semiconductor interface. SIMS results showed arsenic and gallium diffusion into the $WSi_{0.45}$ and tungsten diffusion into the GaAs. This was a small effect compared to the case in which a high dose through-implantation preceded the annealing step.

Figure 1 shows ion-channelling spectra taken from a 400 Å $WSi_{0.45}$–GaAs sample implanted with 50 keV O^+ ions at a dose of 5×10^{16} cm^{-2}. Prior to annealing there is a damage peak visible in the near-surface region of the GaAs—this is

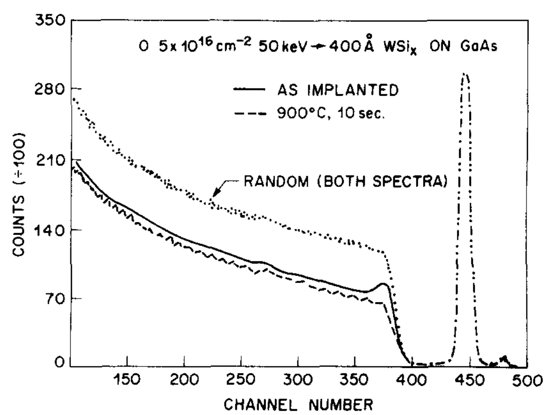

Fig. 1. Ion-channelling spectra before and after annealing (900 °C, 10 s) from a 400 Å $WSi_{0.45}$–GaAs sample implanted with oxygen (5×10^{16} cm^{-2}, 50 keV).

removed by the standard anneal necessary for implant activation (900 °C, 10 s). There is little evidence for any change in the WSi_x film. Figure 2 shows a collage of TEM cross-sections for two oxygen doses through the WSi_x, both before and after annealing. A comparison of the as-implanted samples shows that no amorphous regions have been formed in the GaAs, and that the metal–semiconductor interface appears degraded in the higher dose sample. After annealing, a buried band of defects forms in the lower dose sample—this is typical of highly disordered GaAs. A TRIM simulation shows that the mean range of oxygen in this structure is approximately 550 Å (*i.e.* 150 Å below the $WSi_{0.45}$–GaAs interface), with a straggle of approximately 320 Å. The buried band of defects obvious in Fig. 2 therefore corresponds to disorder extending from the peak in the damage distribution to the end of range. There actually appears to be less damage remaining in the higher dose sample, which shows a variety of rod-like defects and dislocation loops. This might result from beam-induced heating of the sample during the implantation step.

SIMS results showed interdiffusion at the interface upon annealing. Figure 3 shows the atomic profiles of tungsten, oxygen and gallium in a sample implanted with oxygen (5×10^{16} cm^{-2}, 50 keV), both before and after 900 °C, 300 s annealing. The as-implanted sample appears to show knock-on of tungsten at the 10^{20} cm^{-3} level, whereas after annealing there is diffusion of gal-

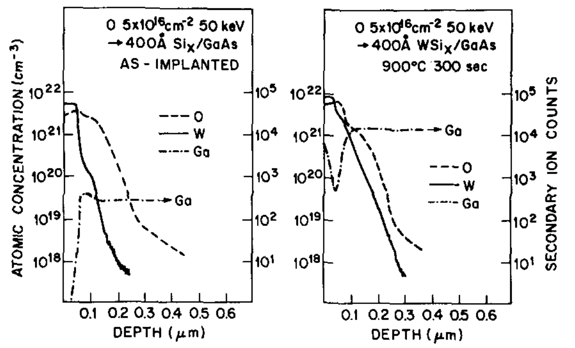

Fig. 3. SIMS atomic profiles of oxygen, tungsten and gallium in 400 Å in $WSi_{0.45}$–GaAs samples implanted with oxygen (5×10^{16} cm^{-2}, 100 keV), before and after annealing at 900 °C for 10 s.

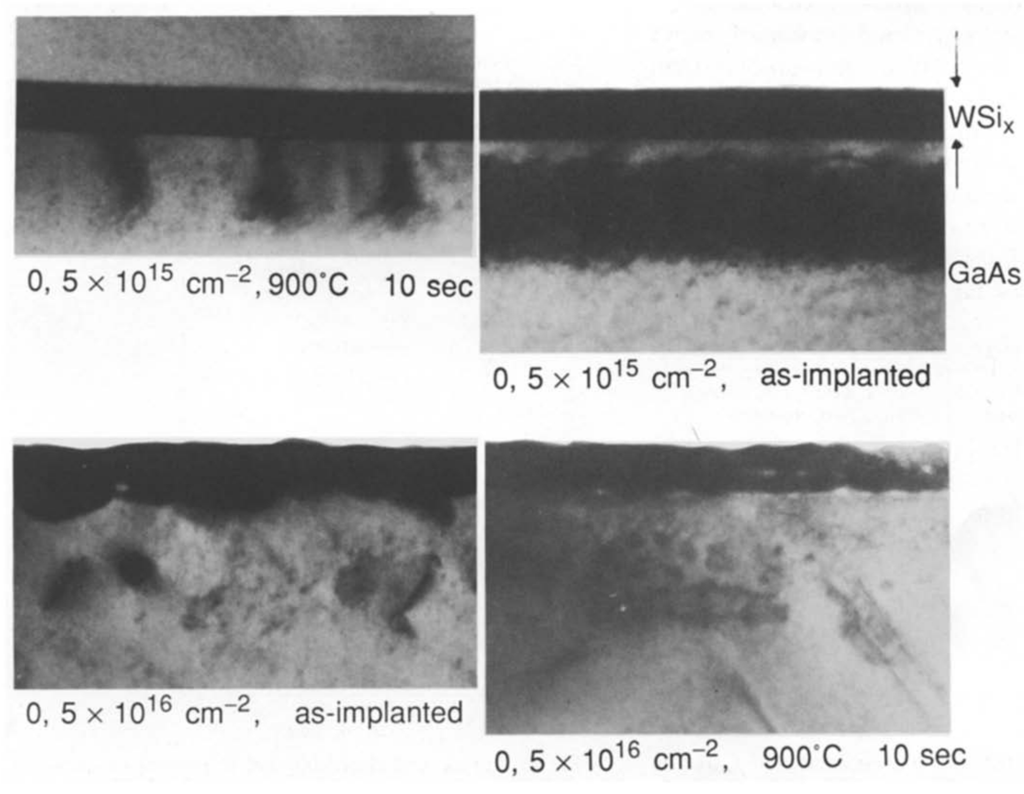

Fig. 2. TEM cross-sections from 400 Å $WSi_{0.45}$–GaAs samples after implantation with oxygen at 5×10^{15} cm^{-2} (top left) and 5×10^{16} cm^{-2} (bottom left), and after subsequent annealing at 900 °C for 10 s (top right and bottom right respectively).

lium into the $WSi_{0.45}$, no apparent motion of the implanted oxygen and more significant diffusion of tungsten into the GaAs within approximately 500 Å of the interface. To get a clearer picture of the amount of tungsten and silicon knocked into the GaAs, we prepared other samples in which the WSi_x was removed by NF_3 reactive ion etching after the oxygen implantation step. This allows SIMS profiling with improved sensitivity and depth resolution. Figure 4 shows the atomic profiles of tungsten in GaAs after oxygen implantation at 5×10^{15} and 5×10^{16} cm^{-2}. The amount of tungsten scales with the oxygen dose, which implies that for the doses of silicon or selenium used in GaAs device fabrication ($(3-8) \times 10^{12}$ cm^{-2} for channel formation), the amount of tungsten knocked into the GaAs would be less than or equal to 10^{16} cm^{-3} to depths less than or equal to 500 Å. Since the peak doping levels in the GaAs channel are between 2×10^{17} and 6×10^{17} cm^{-3}, this implies that ion-induced intermixing is not significant for through-implantation in GaAs device fabrication.

Similar results were obtained for silicon knock-on under the same conditions. Figure 5 shows SIMS profiles of silicon after through-implantation of oxygen at two different doses. Once again there is a significant amount of silicon incorporated into the GaAs, even more so than was the case with tungsten because of the much lower mass of silicon. Even though the amount expected to be knocked on for device level doses would now be of the same order as the doping in the channel, the depth of these silicon ions places them in the zero-bias region of the carrier profiles. In the case of high dose through-implantation, very little of the knocked-on silicon becomes electrically active after annealing. Figure 6 shows the atomic and electrically active silicon concentrations after oxygen through-implantation and subsequent annealing at 900 °C for 10 s. Less than 0.1% of the silicon becomes active, presumably because of the high level of disorder in the interfacial region after such high dose implantation. It must be remembered that it is point defects in GaAs that control the degree of electrical activity of implanted ions, but the presence of a high density of visible defects in TEM implies also the presence of a significant point defect concentration.

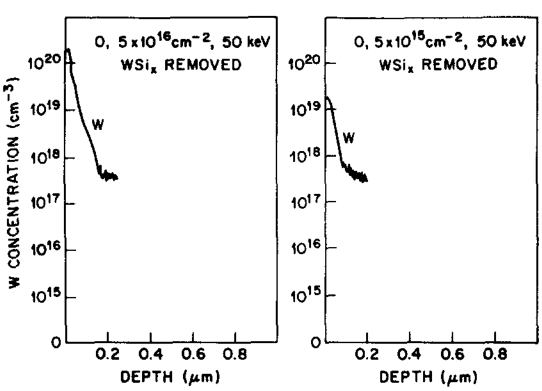

Fig. 4. SIMS profiles of tungsten knocked into GaAs by through-implantation of 400 Å of $WSi_{0.45}$ on the GaAs surface by 50 keV O^+ ions at doses of 5×10^{16} cm^{-2} (left) and 5×10^{15} cm^{-2} (right).

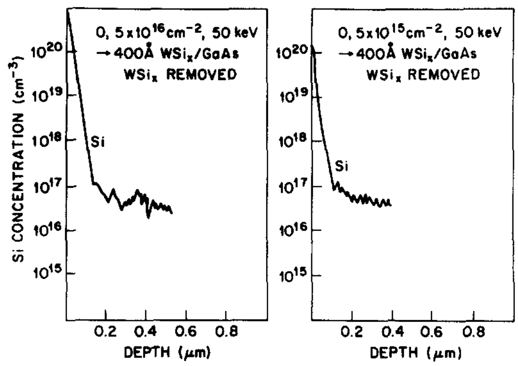

Fig. 5. SIMS profiles of silicon knocked into GaAs by through-implantation of 400 Å of $WSi_{0.45}$ on the GaAs surface by 50 keV O^+ ions at doses of 5×10^{16} cm^{-2} (left) and 5×10^{15} cm^{-2} (right).

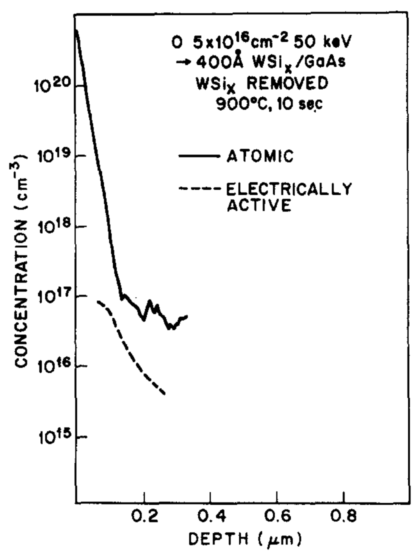

Fig. 6. Atomic and electrically active profiles of silicon in GaAs after through-implantation of 400 Å of $WSi_{0.45}$ on the GaAs surface by 50 keV O^+ ions at a dose of 5×10^{16} cm^{-2} and subsequent annealing (900 °C, 10 s).

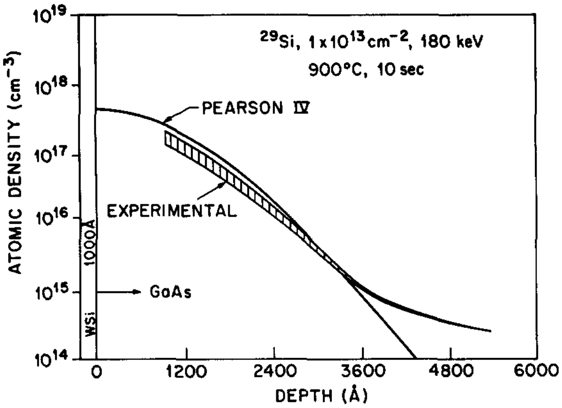

Fig. 7. Theoretical and experimental carrier profiles in GaAs after through-implantation of 1000 Å of $WSi_{0.45}$ on the GaAs surface with silicon (1×10^{13} cm^{-2}, 180 keV) and subsequent annealing at 900°C for 10 s. The shaded region represents the range of carrier profiles measured at 12 spots over a wafer 2 inches in diameter. The Pearson IV distribution is the theoretically predicted ion distribution.

It would be expected that lower dose through-implantation would lead to better percentagewise activation. Figure 7 shows the range of carrier profiles obtained over a semi-insulating GaAs wafer 2 inches in diameter, coated with 1000 Å of $WSi_{0.45}$, implanted with silicon at a dose of 1×10^{13} cm^{-2} (180 keV) and annealed at 900°C for 10 s. The distribution of profiles is relatively tight and the activation is comparable with that of direct silicon implantation under the same conditions. This implies that knock-on of tungsten or silicon is not significant under these conditions. The spread in carrier profiles is also comparable with that obtained by direct silicon implantation, and emphasizes again the feasibility of through-implantation with the WSi_x acting as an encapsulant for the activation anneal.

4. Conclusions and summary

Through-implantation of WSi_x by silicon for creation of doped regions in GaAs, or by oxygen for isolation, has been investigated. Given a sufficiently uniform WSi_x deposition, the activation characteristics of silicon appear similar to those of direct implantation into a bare GaAs substrate. For ion doses around 5×10^{16} cm^{-2} there is significant knock-on of both tungsten and silicon into the GaAs, although extrapolation to device level doses would imply that this is not a problem.

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