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Mass and energy distribution of negatively and positively charged small cluster ions sputtered from GaAs(100) by 150 keV Ar^+ bombardment

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ABSTRACT

Mass and energy distribution of positively and negatively charged small Ga_xAs_y cluster ions consisting of up to six atoms sputtered from a GaAs(100) surface after 150 keV Ar^+ ion bombardment are reported. Positively charged ions contain a larger fraction of Ga atoms while negatively charged ions are rich in As. Measured energy distributions display a maximum at low kinetic energies of a few eV followed by a steep decrease with increasing energy which is more pronounced for larger ions.

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1. Introduction

Ion bombardment of solid targets results in the emission of sputtered atoms, ions and polyatomic species. Sputtering has wide-spread applications, e.g., in plasma-chemical etching processes and for the deposition of functional films [1,2]. The sputtering process is well understood and described within the collision cascade model [3,4]. Many sputtering experiments have been carried out with metals and metal alloys. In this communication we report new results of an experimental investigation of sputtering from a gallium arsenide (GaAs) surface by 150 keV Ar^+ ion bombardment. Gallium arsenide is an important semiconductor with applications in microelectronics and it is used to manufacture devices like light-emitting diodes, laser diodes, and solar cells [5–7].

In order to increase the understanding on sputtering and ionization processes occurring on the surface, a pure GaAs(100) surface was bombarded by 150 keV Ar^+ ions and the mass and energy distribution of sputtered ion species was recorded. Even though plenty of energetic ion bombardment experiments have been done on metal surfaces [8,9], detailed observations employing semiconductor surfaces are still lacking [10–15].

The energy distribution of the sputtered particle carries important information about the interaction phenomena and its ionisation. A theoretical model for the energy of ejected particles was developed by Thompson [16,17]. Accordingly, the energy distribution of sputtered atoms is given by,

$$\frac{dN(E)}{dE} \propto \frac{E\cos\theta}{(E+E_b)^p} \tag{1}$$

where $N(E)$ is the number of sputtered particles with kinetic energy E, E_b is the surface binding energy, θ is the emission angle with respect to the surface normal, and $p \approx 3$. The predicted energy distribution has a maximum at $E_{max} \approx E_b/2$ and asymptotically drops off with E^{-2} [16–18]. For sputtering of clusters composed of n atoms a narrower energy dependence with $p \approx 3n$ has been discussed [18,19]. A statistical model for the energy distribution of sputtered clusters was derived by Können et al. [20].

Previous measurements at low bombarding energies of a few keV have shown that a significant fraction (up to about 4 %) of the sputtered Ga atoms is ionised [21]. Much smaller fractions are observed for As^+, Ga^-, and As^- ions [14]. In general, sputtered species are in their neutral ground state, in a neutral excited state, or in an ionized state which can be positively or negatively charged. When leaving the surface, the ejected species continue for a while to interact with the surface which may involve interaction with delocalized valence electrons and/or localized core electrons [22]. Electronic friction and electron promotion processes may contribute to the exchange of electrons. Other mechanisms that are frequently discussed in this respect are resonance ionisation, resonance neutralisation, and Auger-type processes [23–25]. Within the resonance tunneling model, the escape probability P to survive in its initial charge state is derived as [24]

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$$P = \exp(-v_0/v_\perp) \quad (2)$$

where v is the velocity of the ejected ion, $v_\perp = v\cos\theta$ is the velocity component with respect to the surface normal, and $v_0 = A/a$ is a constant that depends on the transition rate A and the reciprocal mean interaction distance a. Experiments investigating the survival of excited states in front of solid surfaces yield typical values of $v_0 \approx 10^4 - 10^5$ m/s [25–27] which appears reasonable if $A \approx 10^{14} - 10^{15}$/s and $a \approx 1$ Å^{-1} = 10^{10}/m is assumed. A more thorough derivation of the ionisation probabilities P^+ and P^- of positively and negatively charged ions, respectively, and the dependency on the work function Φ yields [28–32]

$$P^+ = \frac{2}{\pi}\exp\left[-(I-\Phi)/\epsilon_0^+\right] \quad \text{and} \quad P^- = \frac{2}{\pi}\exp\left[-(\Phi-A)/\epsilon_0^-\right] \quad (3)$$

where I is the ionisation energy, A is the electron affinity, $\epsilon_0 = \hbar\gamma v_\perp/C_1\pi$ depends on $v_\perp$, $\hbar$ is Planck's constant, γ is a reciprocal interaction distance, and C_1 is a constant which is determined by the position in front of the surface where the effective energy difference is taken [28]. Eq. (3) predicts a velocity-dependent ionisation fraction which is in qualitative agreement with Eq. (2) and an exponential scaling of the ion yield with work function ϕ. Such an exponential work function dependency was verified during sputtering of Si by Cs^+ ion irradiation [15,33–37]. A different model assuming a short-lived electron–hole plasma with a temperature T_e which develops during the collision cascade yields similar expressions but with a velocity-independent $\epsilon_0 = kT_e$, where k is the Boltzmann constant [36,37].

In this paper we present new results for the sputtering of positively and negatively charged Ga_xAs_y ions with $n = x + y$ up to 6 by 150 keV Ar^+ bombardment of a GaAs(100) surface. Mass and energy distributions of sputtered ions are reported. The results provide new insights into the sputtering of ions and the ion-surface interaction.

2. Experiment

The experimental details have been described previously [19]. Energetic Ar^+ ions are produced in a cold Penning ion source and accelerated by a 400 kV ion accelerator. The ion beam enters the target chamber through a 3 mm (diameter) entrance orifice. The experimental chamber is maintained at a base pressure of 8×10^{-9} mbar. The target consists of a chemically clean and polished GaAs(100) sample which is bombarded by 150 keV Ar^+ ions. It can be rotated in such a way that the angle of ion incidence can be changed [38,39]. In the present study, the ion beam hits the target at 22.5° with respect to the target surface normal (Fig. 1). A commercial electrostatic secondary neutral (SNMS) quadrupole mass spectrometer (HIDEN EQS) with a mass range up to 510 amu has been employed for detection of ionized species [40–42]. The mass spectrometer is equipped with an electrostatic energy analysis and operated in the pulse counting mode. The built-in energy filter is a 45° sector field electrostatic energy analyzer with a radius of 7.5 cm; it has an energy range of up to 100 eV per charge unit and an energy resolution of 0.25 eV (FWHM). The analyser is positioned at 45° with respect to the ion beam and 30° out of the target plane. The target is kept unbiased during the experiment and the ion beam current is maintained constant at about 2 μA during the experiment. Singly charged positive and negative sputtered ions are observed and analysed using the EQS detector. The experiments were carried out at room temperature.

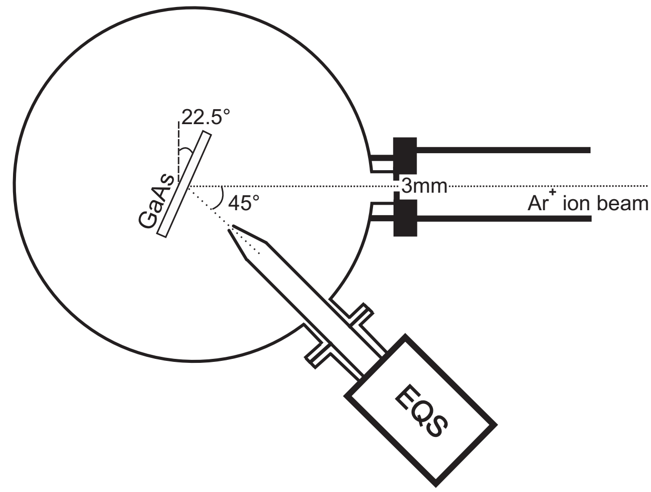

Fig. 1. Experimental set-up (schematic).

3. Results

3.1. Mass distribution

Measured mass distributions of positively and negatively charged Ga_xAs_y ions sputtered by 150 keV Ar^+ ion bombardment are displayed in Figs. 2 and 3. GaAs is composed of two stable ^{69}Ga and ^{71}Ga isotopes with mass numbers $m = 69$ (a = 30.05 %) and $m = 71$ (b = 19.95 %), respectively, and one ^{75}As isotope with mass number $m = 75$ (c = 50 %), where a, b, and c are relative abundances (Table 1). The mass spectrum of positively charged monomers shows two peaks at mass numbers m = 69 and 71 which correspond to $^{69}Ga^+$ and $^{71}Ga^+$ ions. By contrast, the mass spectrum of negatively charged monomers is dominated by a single major peak at mass number m = 75 corresponding to $^{75}As^-$ ions. The mass spectrum of positively charged dimers with two atoms is composed of Ga_2^+ ions at m = 138, 140 and 142 while the mass spectrum of negatively charged dimers is dominated by $GaAs^-$ ions at m = 144 and 146 and As_2^- ions at m = 150. The mass spectrum of positively charged trimers with three atoms is dominated by Ga_3^+ (m = 207, 209, 211, 213) and Ga_2As^+ (m =213, 215, 217) ions. Mass spectra of negatively charged trimers display pronounced peaks of Ga_2As^- (m = 213, 215, 217), $GaAs_2^-$ (m = 219 and 221), and As_3^- (m = 225) ions.

The main peaks in the mass spectra of positively or negatively charged Ga_xAs_y ions with four atoms ($x + y = 4$) are positively charged Ga_4^+ ions at m = 276, 278, and 280, Ga_3As^+ or Ga_3As^- ions at m = 282, 284, and 286, $Ga_2As_2^+$ or $Ga_2As_2^-$ ions at m = 288, 290, and 292, and negatively charged $GaAs_3^-$ ions at 294 and 296 (Table A1). Neither As_4^+ nor As_4^- ions have been detected (Fig. 3).

Mass spectra of positively or negatively charged cluster ions with five atoms ($x + y = 5$) are dominated by Ga_4As^+ ions at m = 351, 353, 355, and 357 or $Ga_3As_2^-$ ions at m = 357, 359, 361, and 363, respectively (Table A1). Positively charged $Ga_2As_3^+$ ions appear at m = 363 and 365. Lastly, the mass spectra of positively or negatively charged cluster ions with six atoms ($x + y = 6$) are largely composed of positively or negatively charged Ga_5As ions in the mass number range m = 420–430, positively or negatively charged Ga_4As_2 ions at mass numbers m = 426–434, and negatively charged $Ga_3As_3^-$ ions at m = 434, 436, and 438 (Table A2). There is some evidence for the appearance of negatively charged $GaAs_5^-$ ions at m = 444 and 446. Mass spectra of negatively charged $Ga_xAs_y^-$ clusters with five and, in particular, six atoms should be considered with care due to their low statistical significance (Fig. 3).

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