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Ion beam sputtering of germanium – Energy and angular distribution of sputtered and scattered particles

Rene Feder*, Carsten Bundesmann, Horst Neumann, Bernd Rauschenbach

Leibniz-Institut für Oberflächenmodifizierung e.V., Permoserstraße 15, D-04318 Leipzig, Germany

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ABSTRACT

The energy and angular distributions of scattered and sputtered particles produced by ion beam sputtering of a Ge target under variation of geometrical (incidence angle of primary ions and emission angle of secondary particles) and ion parameters (ion species (Ar, Xe) and energy (0.5–1.5 keV) are presented.

Several sets of Ge thin films are deposited and their thickness is measured by profilometry to determine the angular particle flux distribution of the sputtered particles. The particle flux distributions are of cosine-like shape and tilted in forward direction and the tilt of the maximum position increases with decreasing energy of the primary ions and increasing incidence angle.

The energy distributions of the sputtered and the scattered ions are measured with an energy-selective mass spectrometer. The average energy of the sputtered ions increases with increasing incidence angle of the primary ions and with increasing emission angle, but is nearly unaffected by the species of the primary ions and their energy. The energy distribution of the scattered Ar ions reveals high energetic maxima that originate in direct scattering between Ar/Ge and Ar/Ar and which shift with increasing emission angle to higher energies. For Xe ion bombardment, there are only maxima for Xe/Xe scattering observed.

All experimental data are compared with Monte Carlo simulations done with the well-known TRIM.SP code.

1. Introduction

The ion beam sputter deposition (IBD) technique is a PVD technique for the production of high quality thin films with tailored properties. In IBD, the energy and mass of the primary ions, the mass of the target atoms and the process geometry lead to different angular and energy distributions of the sputtered and scattered particles and therefore to different thin film properties [1–3]. A systematic analysis of the properties of these film forming particles is necessary for further process adaption.

The present report focuses on the energy and angular distributions of the sputtered and scattered particles for ion beam sputtering of a Ge target. The flux distributions of sputtered Ge particles, the energy distributions of sputtered Ge ions and the energy distributions of scattered primary ions are measured under variation of the process geometry (incidence and emission angle), the primary ion energy (0.5–1.5 keV) and the ion species (Ar, Xe). These data are compared with simulation results, based on the Monte Carlo code TRIM.SP [4].

Ge was chosen as target material because it is a monatomic semiconductor and it is known that semiconductors turn to an amorphous state under ion bombardment, while a metal target like Ag stays polycrystalline [5]. Therefore, different results to those found for Ag [6] can be expected. Additionally, Ge does not have the restrictions known for Si regarding the measurements with the energy-selective mass spectrometer (ESMS) [7]. For Si, the ESMS is not able to differentiate between the mass of Si and the mass of N_2-molecules from the residual gas, what leads to an overlay of the energy distributions. Besides, Ge is important for infrared optics and micro electronics.

Until now, there are no studies on the energy distribution of sputtered and scattered particles from Ge for low energy ion bombardment and only a few other semiconductors where studied. Pellet et al. [8,9] studied the angular resolved energy spectra of particles sputtered from a Si target, but only under a fixed ion incidence angle. Other studies, like Goehlich et al. [10,11] only focus on metal targets. There also exist theoretical studies predicting the anisotropic energy distribution of sputtered particles for oblique incidence [12].

The angular distributions of Ge particles sputtered from a Ge target have been reported by Andersen et al. [13] and Chini et al.

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* Corresponding author. Tel.: +49 (0)341 235 4021; fax: +49 (0)341 235 2313.
E-mail address: rene.feder@iom-leipzig.de (R. Feder).

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[14]. Both studies show over-cosine angular distributions, even for primary ion energies down to 0.6 keV. The absolute sputter yields of Ge for different energies and primary ions were studied by Rosenberg et al. [15] and Laegreid et al. [16].

Recently, we have reported results for sputtering of Ag targets with Ar and Xe ions under variation of ion incidence angle and primary ion energy carried out with the same setup [6,7]. The correlation of the primary and secondary process parameters and electrical and optical properties of the Ag films have also been shown [3].

For the energy distribution of sputtered atoms from a collision cascade the Thompson relationship [17] can be used, predicting the energy of a sputtered particle to be proportional to $E/(E+U)^3$, where U is the surface binding energy of the target atoms.

The collision cascade theory also predicts an isotropic distribution of recoil atoms in the target if it is bombarded by ions at normal incidence. In this case a cosine-type angular distribution of sputtered particles is predicted [18]. Additionally, simulations and experimental results indicate an energy dependence of the angular distribution [19–21], because for low primary ion energies the collision cascade is not completely developed. Consequently, the angular distribution of recoil atoms is not isotropic, resulting in a changed angular distribution (heart-, under- or over-cosine types) [5,13].

2. Experimental conditions and simulation

Fig. 1 shows a schematic sketch of the vacuum deposition chamber. The set up provides the possibility to vary the primary ion incidence angle (α) and the polar emission angle (β). Therefore, the target and the ion source are mounted on rotary tables with an identical rotation axis. Additionally, a sample holder can be mounted in the chamber for thin film deposition. The ion source is an in house development RF type broad beam ion source [22]. A more detailed view on the experimental set up is given elsewhere [6,7].

Ar ions and Xe ions with energies between 0.5 keV and 1.5 keV are used to sputter the Ge target for different incidence angles (0°, 30° and 60°). For the determination of the particle flux, polar emission angles between −40° and 90° in steps of 10° are investigated. Due to the dimensions of the ion source and the ESMS, the emission angle for the measurements of the energy distribution is limited to 60°, 30° or 0° for primary ion incidence angles of 0°, 30° or 60° respectively.

For the determination of the particle flux distributions, the sputtered Ge is collected on Si substrates, like described for Ag in previous work [6,7]. The sticking coefficient of the Ge is about 1 [23]. The thin Ge films are all amorphous and the thickness is between 10 nm and 100 nm. Profilometry is used to determine film thicknesses by measuring the step height between the film and the substrate. For step generation, a part of the substrate is covered during the deposition process. The average particle flux can be calculated using the film thickness and the sputter time. The mass density needed for this calculation is measured using RBS (Rutherford Backscattering Spectrometry).

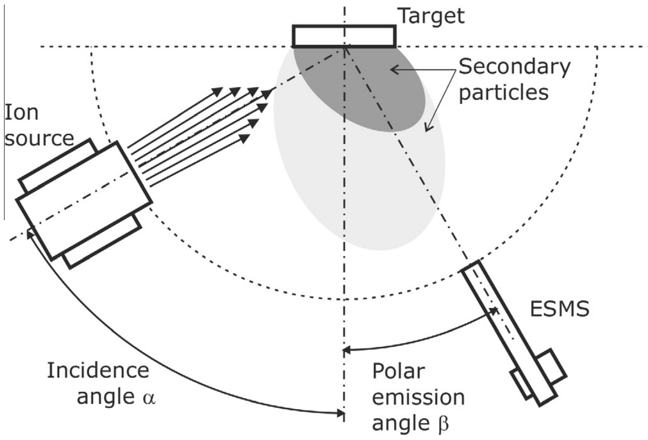

Fig. 1. Schematic sketch of the ion beam sputter setup.

An energy selective mass spectrometer (ESMS) is used to measure the energy distributions of sputtered and scattered ions [6,7]. The ESMS operates in a mass range from 1 amu up to 512 amu and an energy range up to 500 eV with a resolution of 1 amu and 0.5 eV, respectively. For a reasonable interpretation of the ESMS signal, the transmission probability of the ESMS and the ionization probability of the sputtered particles must be taken into account. The transmission probability was simulated by Zeuner et al. [24] for another ESMS that uses quite the similar ion optics. There is unfortunately no work reporting on the ionisation probability of sputtered Ge, but there are generalized considerations like in [25]. Taking both into account, a relative error of about 10% is estimated. Due to this small deviation, the ESMS signal is taken as the energy distribution and the relative error is taken into account in the calculation of the average energies of the sputtered ions.

All experimental data are compared with simulations which are done using the Monte Carlo code TRIM.SP (version trvmc95) [4]. The input parameters are taken from Eckstein [26]. The number of simulated primary ions is 10^8 for each simulation.

3. Results and discussion

3.1. Angular distributions of sputtered Ge particles

In Fig. 2, the experimental and simulated particle flux distributions of sputtered Ge particles are shown for varying primary ion energy E_{ion} and incidence angle α.

The influence of the primary ion incidence angle α on the particle flux distribution for both inert gases is shown in Fig. 2(a and b). For all parameter sets, the Ge particle flux is higher for sputtering with Xe than for sputtering with Ar and the particle flux increases with increasing incidence angle for both ion species, because the total sputter yield is increased [15,16].

In Fig. 2(c and d) the influence of the primary ion energy E_{ion} is shown for an incidence angle of $\alpha = 30°$ for sputtering with Ar and Xe ions, respectively. The Ge particle flux increases with increasing primary ion energy and is again higher for sputtering with Xe ions than for sputtering with Ar ions.

All particle flux distributions show a cosine-like shape that is tilted in forward direction depending on the primary ion energy and the incidence angle. The data can be fitted by

$$\Phi = \Phi^* \cdot \cos^n(\beta + \beta^*) \tag{1}$$

where Φ^* is the maximum value of the particle flux, n is the exponent (under-cosine for $n < 1$ and over-cosine for $n > 1$) and β^* is the emission angle of the maximum value of the particle flux. Table 1 gives an overview of the best-fit parameters. There is no tilting of the cosine distribution for normal incidence. Additionally, the particle flux distribution is nearly perfectly cosine-like for Ar ion bombardment at $\alpha = 0°$ and under-cosine for Xe ion bombardment at $\alpha = 0°$. For other incidence angles, the particle flux distribution is over-cosine and n increases with increasing incidence angle and decreasing primary ion energy. For sputtering with Xe ions, n is higher than for sputtering with Ar ions. The tilting of the particle flux distributions β^*, also increases with decreasing primary ion energy and is higher for Xe bombardment than for Ar bombardment. This