Depth Profiling of GaAs/AlAs Multilayers: Dependence of the Depth Resolution Parameters on the Sputtering Conditions.

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Abstract

Depth resolution in sputter profiling is determined by three fundamental parameters, atomic mixing, surface roughness and information depth. Their dependencies on the type of the sputtering gas (Ar, Xe, SF_6), the ion energy and the incidence angle of the ions, were studied on GaAs/AlAs multilayers using the Mixing - Roughness - Information Depth (MRI) model. Surface roughness and mixing length were also determined independently by means of Atomic Force Microscopy (AFM) and angle resolved AES (ARAES) measurements, respectively. A significant difference was found for the surface roughness in MRI calculations and that of AFM measurements. In contrast, the values of the mixing length determined by MRI and ARAES showed good agreement.

1. Introduction

Recent progress in ion sputter depth profiling with ultrahigh resolution was achieved using low energy SF_5^+ ions in SIMS [1] and AES sputter depth profiles [2, 3]. In the latter case, well defined GaAs/AlAs multilayer samples were used. The depth resolution achieved was 1.6 nm. Application of the MRI model [4, 5] enables the determination of the contributions of the different parameters mixing length (w), roughness (σ), and information depth (λ) to the resultant depth resolution, and to study the variation of these parameters with the sputtering conditions. AES depth profiling was performed by sputtering with ionized Ar, Xe, and SF_6 in the energy range between 500 eV and 3 keV at the incidence angle between 58 and 80 deg.

In this paper we try to confirm the physical nature of the parameters in different sputtering conditions by additional, independent measurements using atomic force microscopy (AFM) for the surface roughness and angle resolved Auger electron spectroscopy (ARAES) for the mixing length.

2. Experimental

The investigations were carried out on a GaAs/AlAs multilayer sample with the following structure (in monolayers, 1 ML = 0.28 nm):

48GaAs/1AlAs/48GaAs/4AlAs/46GaAs/
/20AlAs/GaAs(bulk).

AES depth profiling was performed by sputtering with ionized Ar, Xe, and SF_6 in the energy range between 500 eV and 3keV at incidence angles between 58 and 80 deg. The AES peaks Ga LMM (1065 eV), Al KLL (1393 eV) and Al LVV (68 eV) were used for depth profiling. We also monitored As, and impurities such as O and C. In the case of sputtering with ionized SF_6, F and S were also measured in some experiments.

The obtained depth profiles were analyzed by means of the MRI model [4,5] in order to extract the surface roughness and the mixing length. The values of the information depth were taken from refs. [6,7].

For some samples, the roughness of the surface after profiling was measured directly by means of AFM (NanoScope D3000, Digital Instruments). The experiments were carried out in air in the tapping mode. The analyzed area varied from about 0.5x0.5 μm to 50x50 μm to compare short and long range roughness. In each AFM experiment, 512 x 512 points were measured.

For some etching conditions, the length of the mixing zone was analyzed with angular resolved AES (ARAES). In these experiments, the sample etching was stopped on the tail of third AlAs layer, where the Al concentration

was much lower than that of As. Measurements of the Al and As signal intensities versus the electron escape angle were carried out by the sample tilting in front of the hemispherical analyzer. The results were fitted according to a simple one layer model with the assumption of constant concentration of As versus the depth. The small difference in the information depth between Al (1369 V) and As (1227 eV) was not taken into account because of close kinetic energies of their Auger electrons. The error introduced by these assumptions is smaller than the scattering of the experimental data. The model gives the ratio of Al/As signals as

$$I(Al)/I(As)=const\ [1-exp[-(w/(\lambda \cdot cos\ \theta))]]] \qquad (1)$$

where w is the length of the mixing zone, λ was taken from refs. [6,7] to be 2.32 nm and θ is the emission angle for AES.
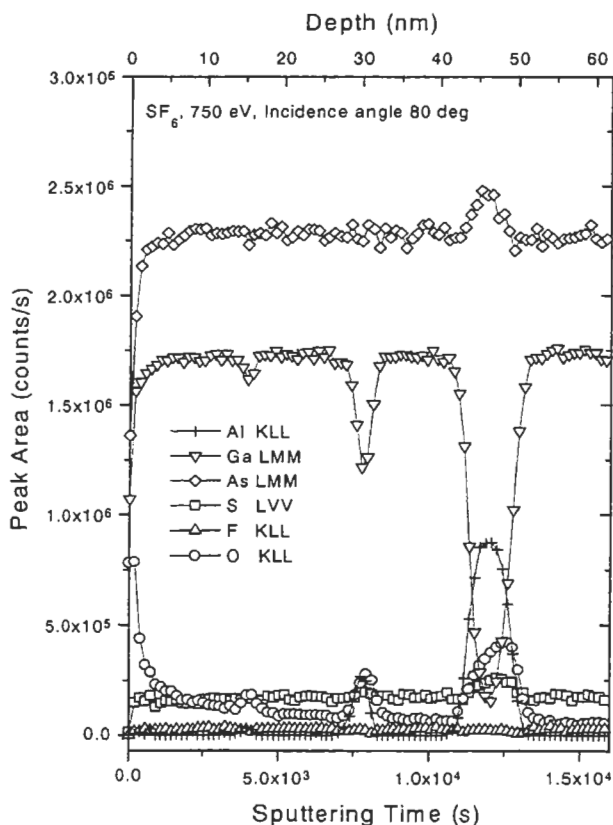

Fig. 1 Typical depth profile The peak areas of the S LVV, O KLL, F KLL, Ga LMM, As LMM and Al KLL are shown versus the sputtering time. Ionized SF_6 has energy 750 eV and angle of incidence 80 deg from the sample normal.

3. Results and Discussion.

Figure 1 shows the peak areas of the AES signals of S (LVV), O (KLL), F (KLL), Ga (LMM), As (LMM) and Al (KLL) in dependence of the sputtering time of the GaAs/AlAs multilayer sample bombarded with ionized SF_6. The ion energy was 750 eV and the incident angle was 80 deg. The oxygen probably originates from H_2O adsorption from the residual gas, and S and F stem from the primary ion beam. The low concentration of F on the surface (the amount of F is about 250 times smaller than that of As) may be explained by formation of volatile F containing compounds. For comparison, sulfur which also originates from the primary ion beam but with about 5 times smaller flux as compared to F in SF_5^+, has a 5 times higher surface concentration than F. This means that sputtering by F is more efficient and presumably is supported by chemical surface reactions. From profiles like those shown in Fig.1, the sputtering time dependence of the Ga and Al peak areas was fitted by using the MRI model. The MRI parameters were extracted and shown in Fig. 2 as function of the sputtering gas, the ion energy and the ion incidence angle. The determination of the parameters is described in detail in ref. [3]. In brief, the depth resolution improves in the sequence Ar, Xe, SF_6, with decreasing primary ion energy and with increasing incidence angle, as demonstrated in Fig. 2. The depth resolution was calculated from the MRI parameters as described in [3].

The improvement of Δz occurs mainly because of changes in the mixing length, w, which, according to MRI fitting results, decreases from 3.2 nm for 3 keV Ar^+ ions and 68 degree incidence angle to 0.4-0.6 nm for ionized SF_6 with 750 eV energy and 80 degree incidence angle. The results of independent measurements of w values with ARAES are shown in Fig. 3. The good agreement between the value of the mixing length obtained from MRI calculations and the fitting of the ARAES measurements with equ. (1) confirms the physical nature of the w value.
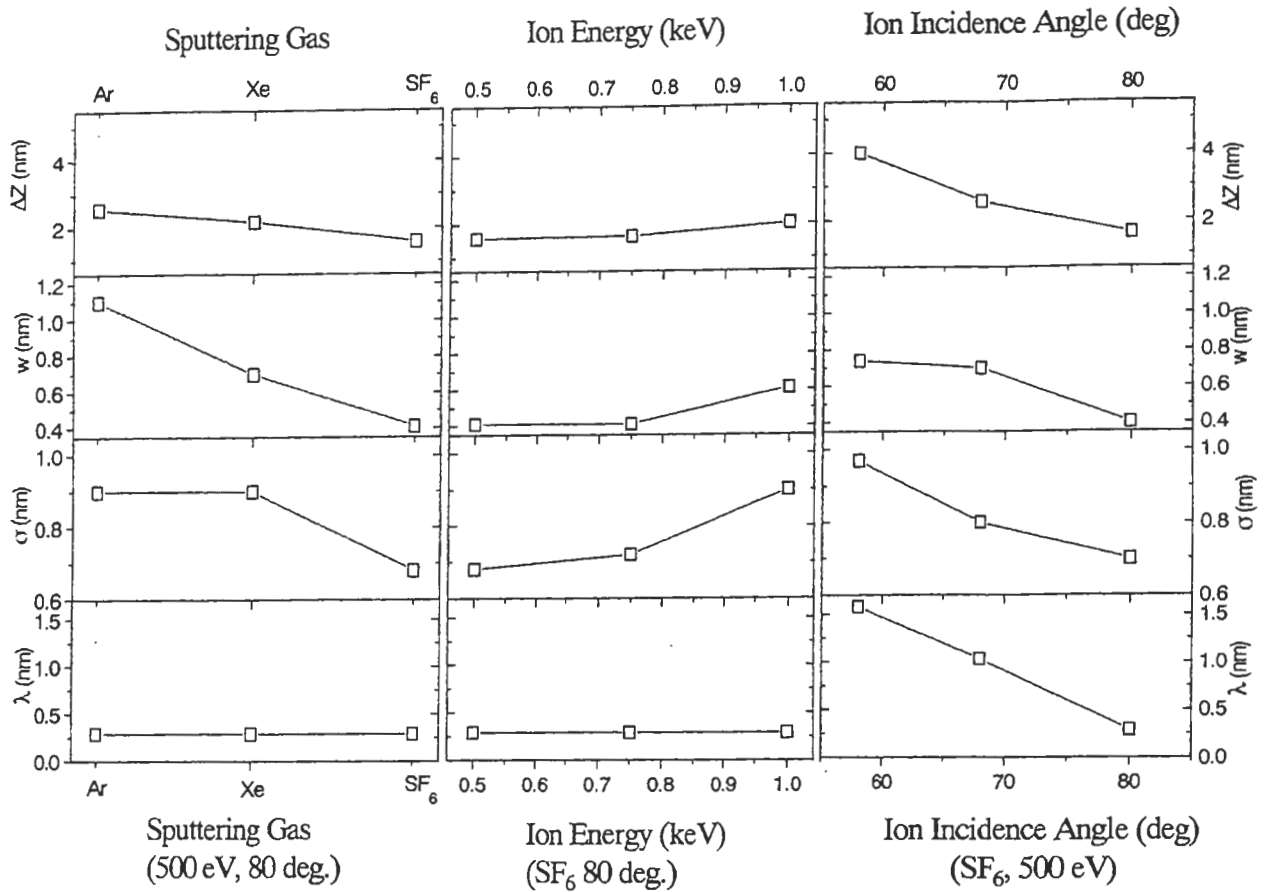
Fig. 2 The selected dependencies of the MRI parameters and calculated depth resolution versus   type of the sputtering gas, ion energy, and ion incidence angle.

Significant difficulties appear in the measurements of the sample roughness. First of all, the changes in MRI calculated surface roughness are not so pronounced as those for the mixing zone (see Fig. 2). The lowest σ value (corresponding to mean square roughness) was about 0.5 nm, a typical value is 0.8 nm. We may also expect some problems due to both AFM measurements and MRI modeling. First, the AFM measurements were performed in air. The native oxide formed at the surface may decrease the roughness. Second, the calculated roughness will   increase if the GaAs/AlAs interface was originally non perfect, because the calculated roughness includes the original interface roughness.   The third reason is due to the approach used in the MRI model, in which the atomic mixing zone is regarded as compositionally homogeneous zone with rigid boundaries [4]. In reality the mixing zone is blurred, and this fact is mainly taken in to account in the roughness parameter.   Therefor this approximation leads to the overestimation of the calculated surface roughness as compared with AFM measurements.

A most important problem is related with the correct extraction of the RMS roughness values determined   from the AFM data. The measured area in AES depth profiling was about 100 X 100 μm. When the AFM measurements are applied to an area of about $1\mu m^2$, we   lose the information on the long range roughness. Application of AFM for roughness measurements at the   larger area is problematic, because of the apparatus bowing of the zero level. We found no reliable way to separate the bowing and the real long range roughness. This may be done with same standard samples, which must be atomically flat at a

range until 50 X 50 μm, but as far as we know such samples are not available yet.
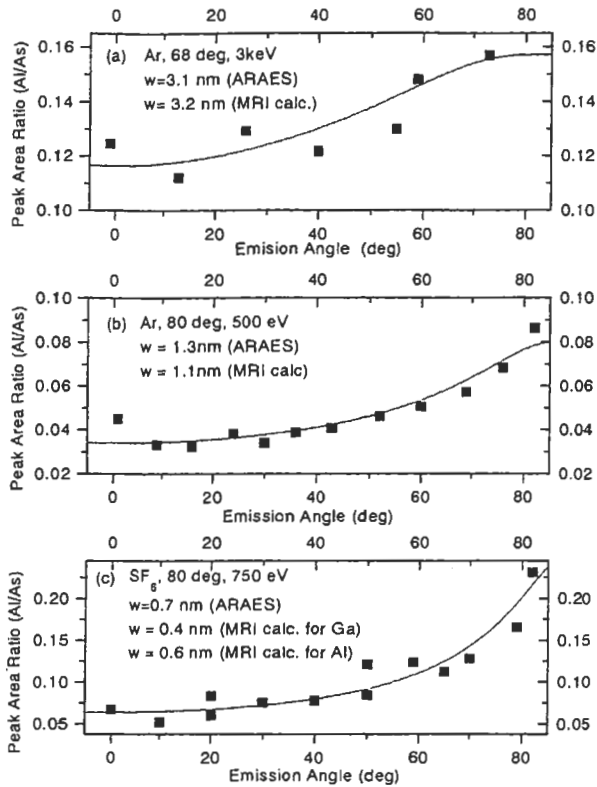

Fig. 3 The ratio of Al KLL / As LMM peak areas versus the emission angle of the Auger electrons. The experiments were carried out after the etching through the third AlAs layer and fitting to equ. (1) to determine the mixing length, as described in the text. The sputtering conditions are shown in the picture together with the mixing length found from the fitting and MRI calculations

The data for short range roughness are shown in Table 1 for the original surface and for some etching conditions in comparison with RMS roughness. The AFM value are lower than MRI ones because of the above mentioned reasons.

Tab. 1 Selected σ values (σ = rms roughness) obtained by means of AFM measurements and MRI modeling.

Sputtering Gas	energy keV	Angle deg	σ AFM nm	σ MRI nm
SF6	0.5	80	0.45	0.7
SF6	0.5	68	0.3	0.8
Ar	1	80	0.3	1.2
Original surface			0.2	

4. Conclusions

AES depth profiles of GaAs/AlAs multilayers were obtained under different sputtering conditions and fitted with the MRI model. The obtained parameters, surface roughness and width of the mixing zone, were compared with independent measurements by AFM and angular resolved AES. The surface roughness measured by AFM is significantly lower than the calculated one, which may be explained by the difficulties with reliable AFM measurements and data processing and by MRI modeling. On the other hand, the good agreement was found between MRI and angular resolved AES results in the determination of the mixing length.

References

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