

Friedrich Schiller Universität Jena
PAF

Dissertation

High-Fluence Ion Beam Irradiation of Semiconductor Nanowires

Andreas Johannes

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Abstract

Hier alles Bla

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1 Introduction

2 Sputtering of Nanowires

This chapter will investigate the sputtering of nanowires. The experiments were conducted together with Stefan Noack and are partially published in his master thesis [?] and in Nano Letters [].

2.1 First results in *Mn* irradiated *GaAs*

Introduction by Mn in GaAs (JPhysD)

2.2 Simulation results

A good understanding of the sputtering of nanowires can be gained by looking at MC simulations results performed with *iradina*. From the discussion of the Sigmund sputter model in chapter ?? a maximum is expected for a certain ion, ion energy and nanowire diameter combination. This can be seen in figure ??a ??b for the examples of Xe^+ and Ar^+ ions respectively irradiating a nanowire at an angle of 45° to the nanowire. For both irradiations a black line indicates the ion range calculated with SRIM and projected on to 45° . The maximum of the sputtering correlates very well with the ion range. It is even better than the first approximation made with the Sigmund sputtering model, which would predict that the sputtering is maximal where the depth of the damage and the radius coincide. However, the Gaussian ellipsoid approximation,

2.3 *Si* nanowire sputtering by Ar^+ irradiation

a Gaussian peak is fitted to the recoil profile for both ions in *Si* [BZH12]. The center of this Gaussian is around $0,7\times$ as far from the impact point as the ion range for the whole energy range investigated here.

This is still $1/\sqrt{2}$ more than the radius of the wire.

The sputter yield is plotted as a function of the nanowire diameter and the ion energy. The difference in sputter yields between Xe^+ and Ar^+

Note that the color profile is not identical as sputtering is about a factor of $2\times$ larger for the denser collision cascades. The ion range calculated using SRIM is plotted as a black curve.

Xe, Ar in Si NW: Energy and Diameter dependent SY

2.3 *Si* nanowire sputtering by Ar^+ irradiation

The experimental verification of this diameter dependent maximum in sputtering was investigated on etched *Si*-nanowire arrays. Figure ?? shows the sputter yield for nanowires plotted vs. their diameter.

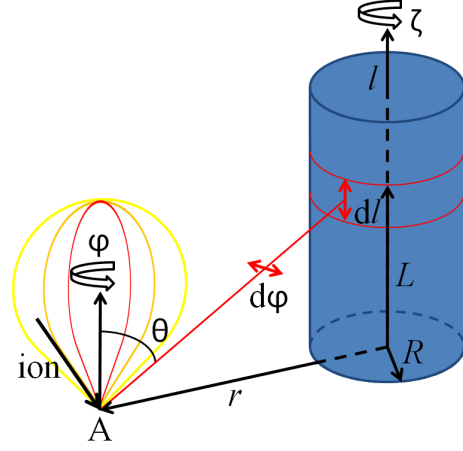
The nanowires were irradiated rotated at an angle of 45° to the ion beam of Ar^+ at 100 and 300 keV. To prevent defect induced density changes and the *Si* from amorphizing, the irradiation stage was heated to 300° , as at this temperature the amorphization threshold becomes arbitrarily high [?]. After a fluence of $10^{16} cm^{-2}$ the change in diameter was close to the resolution limit of the SEM, therefore only the data for the following two irradiation steps of $2 \cdot 10^{16} cm^{-2}$ ions is shown.

2.4 Redeposition

While irradiating a nanowire which is standing perpendicular on a substrate as shown in ?? material will also be sputtered from the substrate.

2 Sputtering of Nanowires

Figure 2.1: Illustration of the redeposition of sputtered material from the substrate point A onto the nanowire with radius R at a height L . Since the wire is rotated around its axis ζ and the whole substrate is irradiated, a rotationally symmetric angle distribution for the sputtered atoms can be chosen.



Some of the sputtered material from the substrate will be redeposited on the nanowire, so that the observable sputter yield will be lower than the actual sputtering. Consider the situation shown in figure 2.1. An ion hits the substrate at point A. A possible path of a sputtered atom is indicated by the red line to a point on the nanowire, redepositing the substrate atom on the nanowire.

The following calculation will estimate how large the redeposition is, by first calculating the probability of a sputtered atom to hit the nanowire P :

$$P = \int_0^{2\pi} \int_0^{\pi/2} H(\theta, \varphi, r, R, L) \tilde{S}Y(\theta, \varphi) \cos(\theta) d\theta d\varphi. \quad (2.1)$$

Where $H(\theta, \varphi, r, R, L)$ is the probability distribution of hitting the nanowire. It is $1/(4\pi)$ if the trajectory along θ and φ from r hits the nanowire with length L and radius R , and zero otherwise. For irradiation at an angle, the angle distribution of the sputter yield $\tilde{S}Y(\theta, \varphi)$ is expected to have a preferential direction along the ion beam [VWMS08]. However, the effective distribution becomes rotationally symmetric (independent of the angle φ) if one neglects the shadowing of the ion beam

2.4 Redeposition

on the substrate, as all points around the wire are irradiated and the wire is rotated around its axis (angle ζ). This means that a rotationally symmetric angle distribution $\tilde{SY}(\theta)$ of the sputtered atoms from the substrate can be used, as indicated by the yellow, orange and red bulbs. A $\cos^\kappa(\theta)$ distribution is chosen, as it forms flattened angle distributions for $\kappa < 1$, which can emulate the rotation of a slanted angle distribution:

$$\tilde{SY}(\theta) = \frac{SY \cdot \cos^\kappa(\theta)}{\int_0^{2\pi} d\tilde{\varphi} \int_0^{\pi/2} \cos^\kappa(\tilde{\theta}) \cos(\tilde{\theta}) d\tilde{\theta}} = SY/c(\kappa) \cdot \cos^\kappa(\theta), \quad (2.2)$$

where the denominator $c(\kappa)$ normalizes the angle distribution function $\cos^\kappa(\theta)$ and SY is the total sputter yield from the surface. The parametrization of $H(\theta, \varphi, r, R, L)$ in φ is straightforward, as the integration bounds for φ are $[-\gamma, \gamma]$ with $\gamma = \arcsin(R/r)$ the angle between r and the tangent to the nanowire in figure 2.2 a). To solve the integration over θ it is useful to express the distance q from the impact point to the base of the nanowire can be expressed as a function of $\rho = R/r$, r and φ :

$$q(\rho, r, \varphi) = r \cdot \sqrt{1 + \rho^2 - 2\sin^2(\varphi) - \sqrt{\cos^2(\varphi)(\cos(2\varphi) - 1 + 2\rho^2)}}, \quad (2.3)$$

to be able to substitute the integration over θ by an integration over the length of the nanowire l . The substitution can be found looking at figure 2.2 b):

$$\begin{aligned} d\theta &= \frac{\sin(\theta)}{\sqrt{L^2 + q^2}} dL \\ \theta &= \arctan(L/q) \end{aligned}$$

2 Sputtering of Nanowires

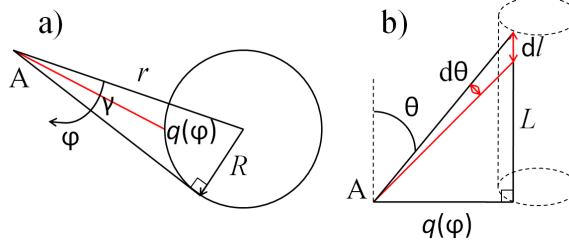


Figure 2.2: a) On the substrate surface R is the radius of the nanowire, r the distance from the point of impact A to the center of the wire, $q(\phi)$ the distance to the wires surface at the base of the wire. The angle between r and the tangent to the nanowire circumference is γ . b) Side on view with θ the angle to the substrate normal of the trajectory to hit the wire at L .

Inserting into equation 2.1 and simplifying yields:

$$P = \frac{2SY}{c} \int_0^\gamma \int_{L_1}^{L_2} \frac{l q^{\kappa+1}}{(l^2 + q^2)^{(\kappa+3)/2}} dl d\varphi. \quad (2.4)$$

With $l^* = L_1 - L_2$ the area hit on the nanowire is now $\pi R l^*$, positioned at the height $L = (L_1 + L_2)/2$ as indicated between the two red lines in figure 2.1. Integrating the probability P to hit the nanowire at each substrate position over the whole substrate area and normalizing it to the area of the nanowire which is hit yields the number of atoms N hitting the nanowire per fluence Φ :

$$N/\Phi = \frac{2SY}{c\pi R l^*} \int_0^{2\pi} d\zeta \int_R^\infty \int_0^\gamma \int_{L_1}^{L_2} r \frac{l q^{\kappa+1}}{(l^2 + q^2)^{(\kappa+3)/2}} dl d\varphi dr. \quad (2.5)$$

The integration can be solved numerically using *numerical tools*. Perhaps counter-intuitively, the result is independent of the nanowire radius R and the height at L at which the deposition is calculated. However, this can be made plausible by looking at figure 2.2. There is no characteristic radius R_c which would change any of the geometric rela-

2.4 Redeposition

tions in 2.2a. Since the integration is over all the $r > R$ and necessarily always starts at $P(R) = 1/2$ and goes to $P(r \rightarrow \infty) = 0$, its result is independent of R . For L it can be argued in figures 2.2b or 2.1 that for a fixed θ , $dL \propto 1/r$ scales as the inverse of the area $dA \propto r$ of the annulus radiating towards the nanowire under that angle. Therefore the redeposition is constant along the whole nanowire length.

3 Summary and Outlook

check: Master Thesis Noack, Ogrisek, Conference proceeding D. Sage, Rutherford, Nordlund

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