HIGH-EFFICIENT WIRE SAWING OF GAAS-WAFERS BY UTILIZATION OF CRACK NUCLEATION MECHANISMS

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1. Introduction
An issue of high relevance in the production of semiconductor wafers is the enhancement of the crystal cutting efficiency and reduction of bow of the cut wafers as an important quality parameter. One of the main reasons for bow is the appearance of a deflection $a_x$ of the wire across its movement during the sawing process. This transverse deflection $a_x$ is controlled by cutting forces acting perpendicular to a plane (cutting plane) defined by feed direction and wire direction. These forces are influenced by process conditions as the cross section of wires and the distribution of slurry in the cutting slit [1]. In addition, as shown recently for a compound semiconductor like GaAs, the forces acting on the wire in the cutting slit are significantly determined by the material properties of the ingot to be cut. A close relationship between fundamental material parameters such as Vickers hardness and scratching behaviour and the complex mechanisms of material removal during wire sawing has been found.

2. Cutting forces during wire sawing
The basic mechanism which underlies material removal during wire sawing is nucleation of micro cracks and their cross linking by the impact of abrasive grains in the lapping slurry. The threshold for the transition from a plastic to a brittle removal mechanism mentioned above is characterized by a critical penetration depth $h_c$ and a corresponding critical stress of the grains according to [2]:

$$h_c = \Theta_1 \cdot \left(\frac{E}{H}\right) \cdot \left(\frac{K_{IC}}{H}\right)^2$$

(1)

with the Young’s modulus $E$, the Vickers hardness $H$ and the stress intensity factor $K_{IC}$. The parameter $\Theta_1$ depends on tool geometry and details of the complex deformation mechanism. To reach this threshold a well defined load $P_c$ must be transferred from the cutting tool (grain) to the material to be cut. So, a counterforce of the same amount acts on the grains and consequently on the wire. The relationship between $h_c$ and $P_c$ simply follows from the hardness formula and is given by [4]:

$$h_c(P) \propto P_c^{\frac{1}{2}}$$

(2)

Depending on their causes, the forces acting on the cutting tool in the cutting slit are divided in external, impressed forces $F$ and constraint forces $Z$ (see fig.1). Their components $Z_x$ and $F_x$ perpendicular to the cutting plane will be in equilibrium under quasi-stationary conditions:

$$Z_x^+ + Z_x^- + F_x = 0$$

(3)

The external forces $F$ on the wires are determined by technological conditions of the cutting process as for example by the
wire tension $\sigma$ in combination with the wire deflection in the cutting plane. The constraint forces $Z^+_{x,}$ and $Z^-_{x}$ perpendicular to the uncovered planes results from the counterforces to the critical loads necessary for setting in the brittle material removal mechanism on this surfaces. They are controlled by the critical penetration depths $h^+_{x}$ and $h^-_{x}$ for the ductile to brittle transition for the $(100)$ and $(\overline{1}00)$, respectively, according to eqs. (1) and (2) [3]:
\[
\frac{h^+_{x}}{h^-_{x}} = \frac{Z^+_{x}}{Z^-_{x}}
\] (4)

For $\alpha \ll 1$ (see fig. 2) the deflection of wires $a_{x}$ perpendicular to the cutting plane is given by [3]:
\[
a_{x} = \frac{p^+_{x} + p^-_{x}}{F_{\sigma}} l_1 l_2 = Cf(z)
\] (5)

with $f(z) = l_1 l_2$; $C = \frac{p^+_{x} + p^-_{x}}{F_{\sigma}}$; $p^+_{x} = \frac{Z^+_{x}}{l_1}$ and $p^-_{x} = \frac{Z^-_{x}}{l_1}$
(see fig.1 and fig.2). $F_{\sigma}$ acts in the wire direction and is determined by the wire tension $\sigma$. The bow of the cut wafers is mainly caused by the lateral deflection $a_{x}$ which according to eq. (5) is composed of a shaping factor $f(z) = l_1 l_2$ related to geometrical parameters (distance between the wire guides, contour of ingot, contact length $l_1$) of the sawing process and a factor $C$ which is controlled by the constraint forces $Z^+_{x}$ and $Z^-_{x}$, i.e. by material properties according to eq. (4).

3. Crack nucleation at Vickers indentations
The ductile to brittle transition in brittle-hard materials can be characterized by a critical penetration depth of an indenter for initiation of cracks [7]. For a Vickers indenter the critical diagonal length for initiation of a radial-median crack system is given by [4]:
\[
d_c = \Theta \left( \frac{K_{IC}}{H} \right)^2
\] (6)

with $K_{IC}$ as the stress intensity factor, $H$ the Vickers hardness and a factor $\Theta$ depending on the geometry of the indenter and the complex deformation mechanism beneath the indenter. Around the indention a system of radial-median cracks is formed which is associated with local plastic deformation and a corresponding network of dislocations even for brittle materials [4]. For GaAs two sets of dislocations with different core structure and Peierls potential are involved in crack nucleation, the $\alpha$- and $\beta$-dislocations which exhibit different mobilities under identical conditions. This can be revealed by DSL-etching of a (001)-oriented specimen with Vickers indentations after heat treatment for stress relaxation at 300°C as represented in fig. 4. The rows of etch pits indicating the displaced dislocations are longer for $\alpha$- than $\beta$-dislocations. It could be shown experimentally, that there also exist two types of cracks propagating parallel to the rows of the $\alpha$- and $\beta$-dislocations, called $A$- and $B$-cracks. As determined experimentally, the $A$-cracks are formed at loads of about 0.1N. The $B$-cracks and the complete radial-median crack system are formed at loads which are roughly an order of magnitude...
greater (see fig. 5). The A- and B-cracks are preferentially formed in \{110\} cleavage planes. This further means that instead of one condition for the ductile-to-brittle transition two conditions must be formulated for GaAs [3]: For Vickers indentations in undoped (100) GaAs the critical lengths of diagonals \(d_A\) and \(d_B\) for crack nucleation in surfaces according to eq. 6 is given by:

\[
d_{A,B} = \Theta_{A,B} \left( \frac{K_{A,B}}{H} \right)^2 \tag{7a,b}
\]

for A- and B-cracks.

At a critical load \(P_A \leq P_B\) characterized by \(d_A \leq d_B\) the A- and B-cracks are formed (see fig. 6). It has been shown by corresponding measurements that for the stress intensity factors in eqn. (7a,b) determining the resistance for crack propagation holds \(K_{A}^{IC} = K_{B}^{IC}\) [3]. Therefore, the crack length \(c_0\) after their nucleation is given by \(c_0(P) \propto P^{3/2}\) with the fracture toughness as the relevant material parameter. Thus, the observed difference in crack formation is assumed to be caused by differences of the dislocation assisted crack nucleation due to the existence of \(\alpha\)- and \(\beta\)-dislocations.

4. Results of single grain scratching tests

The modified criterion for ductile-to-brittle transition implies a dependence of the critical penetration depth of a tool (see eq. 1) on the angle \(\gamma\) of its direction of movement relative to the propagation directions of cracks of type A and B, i. e.

\[
h_c = h_c(\gamma) \tag{8}
\]

This finding was verified by single grain scratching tests on polished (100)-oriented GaAs-surfaces results of which are represented in fig. 7. In addition it was found that \(h(\gamma)\) depends on the geometry of the cutting tool. For roof-shaped diamonds which describe the situation in the slit during wire sawing best, tension forces act parallel to the moving direction creating cracks which propagate perpendicular to this movement [3]. Therefore, the critical penetration depth is high if B-cracks are initiated and low for A-cracks resulting in a two-fold symmetry (see fig. 7). As the scratching angle \(\gamma\) corresponds to the feeding direction \(\omega\), the balance of forces (eqs. 2 and 3) on the wires depends on the feed direction \(\omega\) as well.

5. Consequenzes for the wire sawing technology

GaAs crystallizes in the \(\overline{4}3m\) crystal class. This means that the \((\overline{1}00)\) and \((100)\) planes in fig. 1 are not identical, i. e. B-cracks on \((\overline{1}00)\) are par-
allel to A-cracks on (100) and vice versa. To match the crack pattern on these two planes an inversion and rotation is necessary. With other words: if the critical penetration depths for both planes $h_c^+$ and $h_c^-$ are reassigned to the feeding direction $\omega$, the graphs of $h_c^+$ for (1100) and $h_c^-$ for (100)-plane are not congruent with each other but have to be rotated by an angle of 90° (fig. 8). This finding offers the opportunity to create well defined ratios $h_c^+/h_c^-$ by choosing different feeding directions $\omega$. Consequently, according to eq. 3 the ratio of constraint forces, wire deflection and finally the bow (eq. 4) can be directly controlled.

This is illustrated in fig. 9. The bow is given in dependence on the feeding direction $\omega$ is measured after wire sawing and removal of a damage layer by wet chemical etching. It is obvious that absolute value and sign of bow of the sliced wafer can be defined very precisely by the ratio of the critical penetration depths $h_c^+$ and $h_c^-$ (fig. 8). Interferometrically measured shapes of wafers for different feeding directions are represented in fig. 10. The general profile in the feed direction corresponds to the shape factor $f(z)$ in fig. 3., but is quantitatively determined by the factor

$$C = \frac{P^+ - P^-}{F_\alpha}.$$

From eq. (4) and (5) follows

- $h_c^+ < h_c^- \Rightarrow C < 0$  
  fig.10a
- $h_c^+ = h_c^- \Rightarrow C = 0$  
  fig.10b
- $h_c^+ > h_c^- \Rightarrow C > 0$  
  fig.10c

6. Conclusions

The mechanisms of micro-crack nucleation in GaAs and the respective symmetric properties allow a defined adjustment of the force balance in the cutting slit by using wire direction relative to crystallographic direction of the crystal as a control parameter. Setting the condition $h_c^+ = h_c^- \Rightarrow C = 0$ allows to produce wafers with very small bow. As a side effect of these findings, feed velocity of more than 2mm min$^{-1}$ can be applied. This technology requires single direction of wire movement.

References


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