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Modeling the parameters of the multi-wire cutting mode, ensuring high surface quality of InSb (100) wafers

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The surface preparation processes for InSb plates of the "Epi-ready" class include a number of machining processes that significantly affect the quality of the final products. One of these processes is wire cutting of single crystals. In this study, the issue of calculating the conditions of wire cutting and determining the limiting parameters for the movement of the desktop, as one of the factors affecting the BOW and WARP plates, was studied. The experimental work was carried out to determine the cross-sectional sections of the InSb single crystal required for segmentation, and the cutting speed was calculated for each of them. The practical confirmation of theoretical calculations with an effective change in surface parameters is shown.

Keywords: $A^{III}B^V$, InSb, wire cutting, optical profilometry, wire cutting parameters, calculation of worktable speed.

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Introduction

$A^{III}B^V$ compounds are currently the main materials for the manufacture of focal plane arrays (FPAs) [1], which are created using the technology of epitaxial growth of layers, which requires high-quality substrate surfaces. Obtaining "epi-ready" class $A^{III}B^V$ wafers is one of the main challenges for the development of microelectronics [2]. The technology for producing FPAs consists of many stages, including the mechanical processing of single crystals, which involves main operations such as wire sawing into wafers, subsequent grinding, and chemical-mechanical polishing. Therefore, improving the quality of the wafers requires optimization of the processing regimes at each

stage of their manufacture. The separation of single crystals into wafers is performed by wire sawing. Although this process receives limited attention, it exerts a substantial influence on the surface parameters on the bow (BOW) and warp (WARP) of finished "epi-ready" wafers. This technological operation largely determines the quality of future products. For this reason, multi-wire sawing requires a more detailed analysis regarding its impact on the qualitative characteristics of wafers.

In a previous work [3], the main wafer surface parameters determined during the multi-wire sawing stage – specifically, wafer bow (BOW) and wafer warp (WARP) – were identified. These parameters can either increase or decrease depending on the specified processing

conditions. To identify the degree of significance of this surface parameters, wafers were selected after sawing, grinding, and polishing, allowing the trends in their evolution to be tracked across each technological step.

The main feature in the processing of InSb is that these single crystals exhibit significant bulk stresses. During the mechanical processing of InSb, the depth of the subsurface damaged layer is larger than in Si and GaAs. This requires the removal of a significant layer during grinding and subsequent polishing. "Gentle" sawing regimes can reduce the depth of this structurally damaged layer, leading to material savings in obtaining "epi-ready" wafers.

The main technology for the mechanical processing of InSb relies on multi-wire sawing with a constant stage feed rate. However, based on the analysis in the article [4], it can be hypothesized that varying the cut width of the sample alters both the wire runout and the force exerted by the wire on the sample. A uniform distribution of this force it can be hypothesized would favorably affect the surface parameters. This hypothesis arises from findings indicating

that the surface roughness of a wafer cut by wire sawing is usually nonuniform, which can create problems during subsequent grinding and polishing. Also, the parametric studies presented in the article [4] show that the vibrational displacement of the wire decreases with increasing distance of contact between the wire and the crystal.

Experiment

In the work [5], a model was proposed into which some corrections were introduced considering the conditions of InSb sawing. During the sawing, a wire with a tension T acts on the InSb crystal (Fig. 1). As sawing progresses, the wire deflects by a certain angle α and applies a total force F_{total} to the sample. In the Y -direction, the force of action F_{total} is equal to the reaction force F_{total}^K , since the force with which the wire acts on the InSb crystal equals to the force with which the crystal acts on the wire [6]. Thus:

$$F_{\text{total}}^K = F_{\text{total}} = 2T \sin \alpha. \quad (1)$$

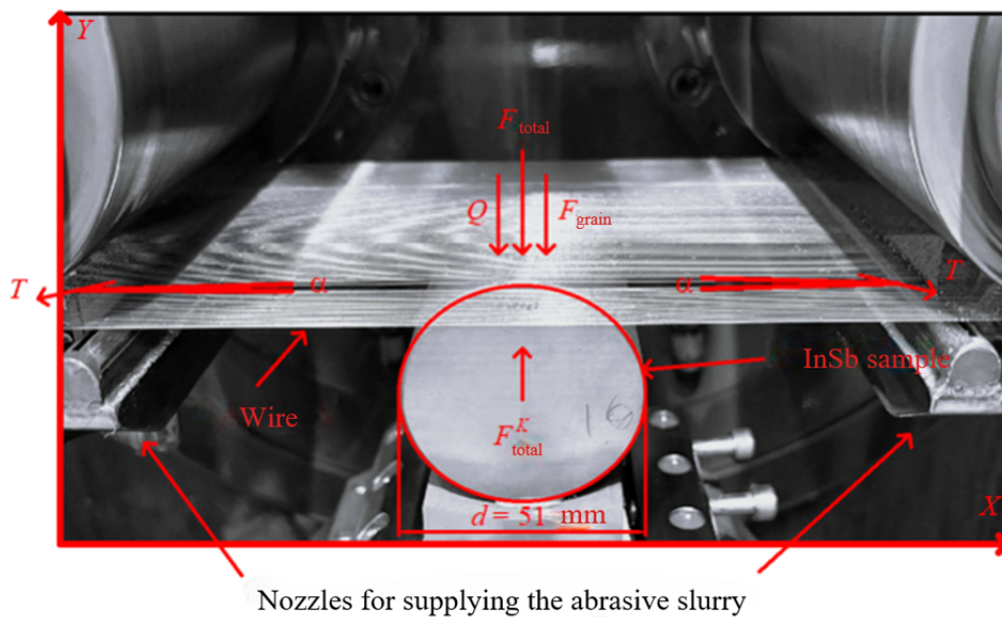


Fig. 1. General view of the InSb sample being cut

The force of the wire's action on the crystal F_{total}^K is not applied to the crystal at a single point, but is distributed over the entire cut width – L' . Let us denote this distribution as – Q . Thus, we obtain the expression:

$$Q = \frac{F_{total}}{L'} = \frac{2T \sin \alpha}{L'}. \quad (2)$$

In addition, a distinct force is applied to each abrasive grain entering the cutting zone. This force can be calculated by dividing the total applied force F_{total} by the number of abrasive grains in the cutting zone. To calculate the number of abrasive particles (N), it is necessary to divide the cut width of the InSb crystal (L') by the distance between the abrasive particles (L_{part}).

$$N = L_o / L_g. N = \frac{L'}{L_{part}}. \quad (3)$$

The force applied to a single abrasive grain, F_{grain} , is obtained by dividing the total applied force F_{total} by the number of abrasive grains (N) located along the entire length of the cut:

$$F_{grain} = \frac{F_{total}}{N} = \frac{2T \sin \alpha}{L_{part}} \times L'. \quad (4)$$

The configuration of the applied forces (F_{total}^K , F_{total} , F_{grain}) in the real process (Fig. 1) is also presented as a vector diagram in Figure 2.

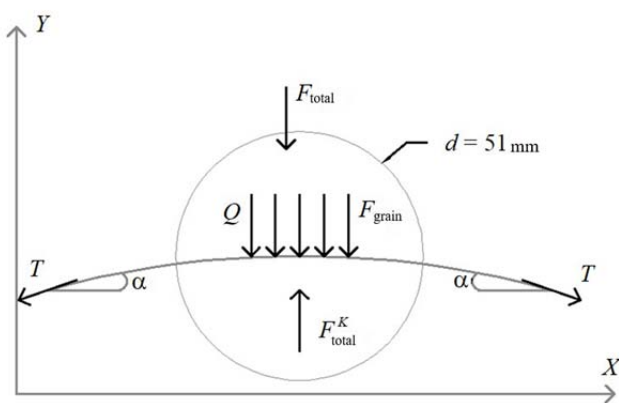


Fig. 2. Vector representation of the forces acting during wire sawing on the InSb sample being cut

Due to the circular cross-section of the InSb single crystal, the cut width L' is not constant and varies as the cutting progresses. The supplied flow of slurry into the cutting zone remains constant; consequently, the same number of abrasive particles enters the wire sawing region, allowing the distance between the abrasive particles L_{part} to be considered constant (const). In such a case, the distribution of the total force acting on the crystal F_{total} directly depends on the cut width of the InSb single crystal. Under conventional sawing conditions with a constant feed rate (table feed rate V_{table}) the variable cut width of the circular InSb crystal causes the force exerted by the wire to also vary. This leads to qualitative variations in the surface topology of the cut wafer (Fig. 3a). These differences manifest themselves as five surface non-uniformity regions when measuring its topology using the Microprof optical profilometry system (Fig. 4). This system enables non-contact topography imaging and measurement of wafer geometric characteristics, such as total thickness variation of the wafer (TTV), bow (BOW), warp (WARP), and total indicator reading (TIR).

To equalize the force exerted by the wire on the single crystal and eliminate these five non-uniformity regions, it is proposed to implement a blockwise sawing method by calculating and adjusting a specific feed rate for each of the blocks. For this purpose, the cross-section of the 51-mm-diameter InSb crystal was divided into 20 blocks. Thus, the height of each block is 2.55 mm (Fig. 3b).

Each block has a cut width limited by its sector, located above and below the block. The cut width for the beginning of each block is indicated in Table 1. Analyzing the surface topology of the wafer after sawing revealed that the five non-uniformity regions on the 51-mm-diameter InSb wafer strictly correlate with the sector indices presented in the table (Table 2).

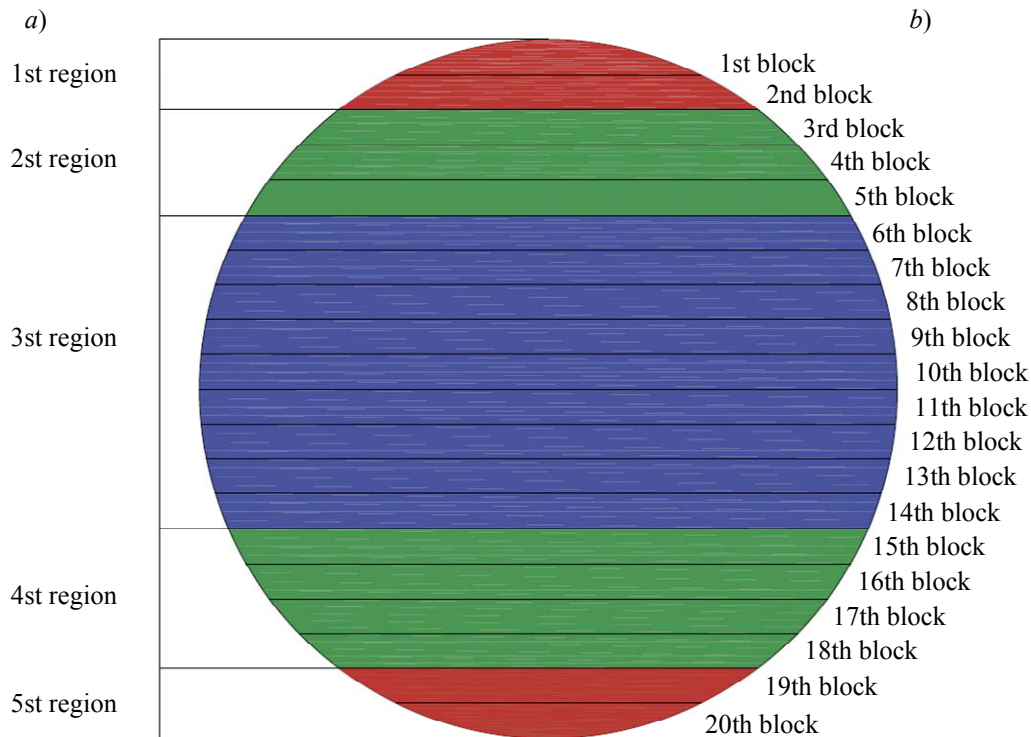


Fig. 3. Schematic representation of the InSb 2'' wafer being cut with division: a) into regions of nonuniformity obtained as a result of measuring the surface of the cut wafer by means of optical profilometry, cut at a constant sawing speed $V_{\text{table}} = 8 \text{ mm/h}$; b) into 20 blocks, for each of which it is necessary to calculate its own value of cut width and sawing speed. Height of each block: 2.55 mm

Table 1

Main variables in the calculation and their values

$V_{\text{table}} = 8 \text{ mm/h}$	–	standard constant table feed rate (mm/h)
V_{block}	–	sawing speed calculated for each of the 20 blocks (mm/h). For blocks No. 1, 20, the sawing speed is taken equal to 8 mm/h
Q	–	value of wire tension (N)
α	–	wire deflection angle (degrees)
F_{total}	–	total force applied by the wire to the sample being cut (N)
F_{total}^K	–	force with which the crystal acts on the wire (N)
L'	–	cut width of the single crystal (total width of contact between the wire and the InSb crystal) (mm)
Q	–	distribution of the force of the wire's action on the crystal per unit cut width (N/mm)
F_{grain}	–	force applied to one abrasive grain (N)
N	–	number of abrasive particles (pcs.)
L_{part}	–	distance between abrasive particles (mm)
n	–	ordinal number of the block; in the calculation formula n varies successively from 1 to 18
l_n	–	n -value of the width of the beginning of the block
k	–	coefficient of the ratio of the average value of the width of block n to the average value of the width of block $n + 1$

Table 2**Results of measuring the width of the beginning of each block**

No. of the region of nonuniformity	No. of the sawing block (n)	Width of the beginning of the block (l_n) (mm)
1	1	0.00
1	2	22.23
2	3	30.60
2	4	36.42
2	5	40.80
3	6	44.17
3	7	46.74
3	8	48.65
3	9	49.97
3	10	50.74
3	11	51.00
3	12	50.74
3	13	49.97
3	14	48.65
4	15	46.74
4	16	44.17
4	17	40.80
4	18	36.42
5	19	30.60
5	20	22.23

For each block, it is necessary to determine the parameters of the sawing process, namely the stage feed rates for a uniform distribution of the total force F_{total} that the wire applies to the InSb single crystal being cut. This can be achieved by calculating the average cut width for each block, then determining the ratio coefficient of the average width of block n to that of block $n + 1$, in order to determine the ratio of the blocks to each other. The resulting coefficient is then successively multiplied by each successive feed rate value. Then blockwise feed rate V_{block} is determined as:

$$V_{\text{bl}} = V_{\text{lb-1}} \times \frac{(l_n + l_{n+1})}{\frac{(l_{n+1} + l_{n+2})}{2}}, \quad (5)$$

where n takes a value from 1 to 18, and $V_{\text{block-1}}$ begins with 8 mm/h for the first calculation value. This parameter was chosen as the initial feed rate, since it corresponds to the constant sawing speed (table feed rate) in the initial process, against which the analytically modified process is compared (Table 3).

Table 3**Calculation of the sawing speed for each block in the process modified on the basis of the calculations**

No. of the sawing block (n)	Width of the beginning of the block (l_n) (mm)	Average value of the cut width for each block (mm)	Coefficient k	Calculated sawing speed for each block V_{block} (mm/h)
1	0.00	11.12	1.00	8.00
2	22.23	26.42	0.79	7.98
3	30.60	33.51	0.87	6.31
4	36.42	38.61	0.91	5.47
5	40.80	42.48	0.93	4.97
6	44.17	45.45	0.95	4.65
7	46.74	47.70	0.97	4.43
8	48.65	49.31	0.98	4.29
9	49.97	50.36	0.99	4.20
10	50.74	50.87	1.00	4.15
11	51.00	50.87	1.01	4.15
12	50.74	50.36	1.02	4.20
13	49.97	49.31	1.03	4.29
14	48.65	47.70	1.05	4.43
15	46.74	45.45	1.07	4.65
16	44.17	42.48	1.10	4.97
17	40.80	38.61	1.15	5.47
18	36.42	33.51	1.27	6.31

End of table 3

No. of the sawing block (n)	Width of the beginning of the block (l_n) (mm)	Average value of the cut width for each block (mm)	Coefficient k	Calculated sawing speed for each block V_{block} (mm/h)
19	30.60	26.42	1.27	7.98
20	22.23	11.12	1.00	8.00

Note: Here k is the coefficient of the ratio of the average value of the width of block n to the average value of the width of block $n + 1$, where n is the block index. Coefficient $k = 1$ for blocks No. 1, and 20, as their sawing speed is initially defined as 8 mm/h. For block No. 10, the coefficient is also $k = 1$, since the ratio of the average value of the cut width for block No. 10 to that of block No. 11 is equal to 1. The coefficient k gradually increases toward 1 from block No. 2 to block No. 10, since the width of block n is smaller than that of block $n + 1$ and successively increases in the indicated range. Conversely, the coefficient k is greater than 1 from block No. 11 to block No. 19, since the width of block n is larger than that of block $n + 1$ and successively decreases in the indicated range.

Results and Their Discussion

To carry out the experiment, a Takatori wire sawing machine equipped with a free abrasive cutting system (an abrasive slurry consisting of oil and silicon carbide powder SiC) was used. Two wire sawing processes were performed on 51-mm-diameter InSb single crystals grown via the Czochralski method under identical technological conditions. The first was conducted at a constant feed rate [7] ($V_{\text{table}} = 8$ mm/h), while

the second utilized the blockwise feed rates (V_{block}) calculated for each block (Table 3).

The first and second sawing processes yielded 50 and 47 wafers, respectively. The thickness of the wafer being cut was ≈ 1 mm. After sawing, the surface topography [8] of all InSb wafers was imaged. The scatter of the surface parameters across the measured wafers remained within a 3–5% range. Figure 4 presents a typical surface topography image for each of the performed processes.

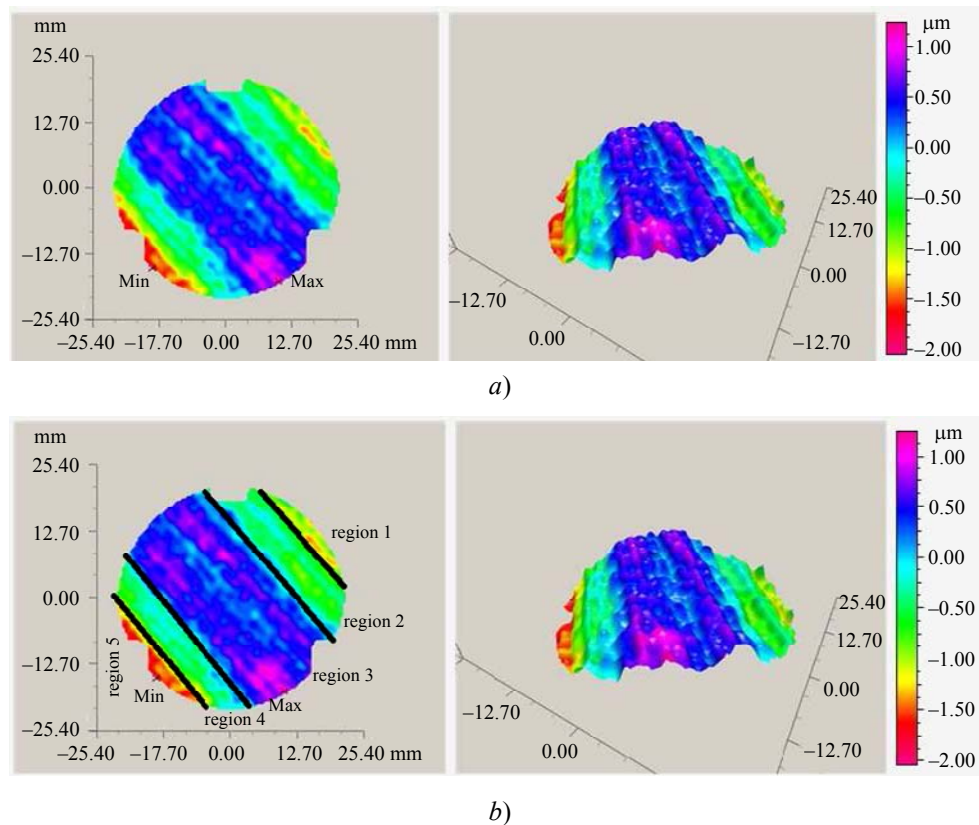


Fig. 4. Surface topography image of an InSb wafer cut at a constant sawing speed $V_{\text{table}} = 8$ mm/h: a) initial surface topography image; b) schematic representation of the division of the wafer into sectors with differing surface quality

This image reveals a distinct bow of the wafer. From the surface topography, the wafer can be divided into five non-uniformity regions, the boundaries of which are marked in the figure with different colors. The measured boundaries of the regions agree well with the scheme proposed in Figure 3.

The calculated wire sawing speeds (Table 3) were entered into the control program for each of the 20 blocks, after which the InSb single crystal

was sawed with subsequent surface topography imaging of the obtained wafer. The result of this measurement is presented in Figure 5.

In this topographic image, the wafer bow is less pronounced. Unlike the results shown in Figure 4, the five previously distinct non-uniformity regions were not observed in this topography. Measurements of the surface parameters [9] for both sawing processes are presented in Table 4.

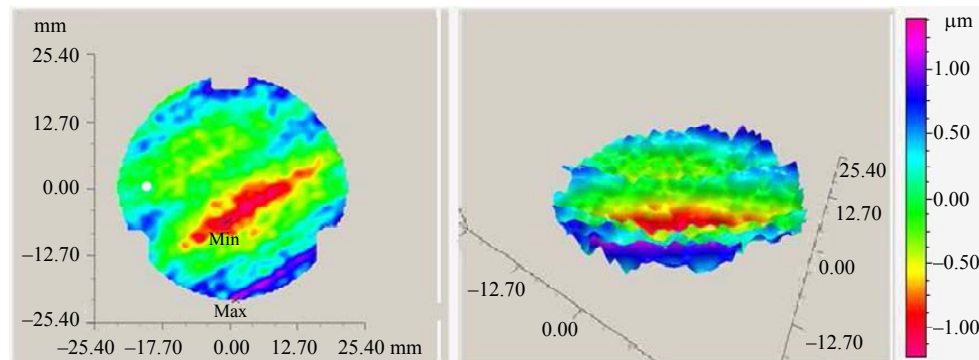


Fig. 5. Surface topography image of an InSb wafer cut at a calculated variable sawing speed

Table 4

Measurement of surface parameters [10] for the sawing process performed at a constant speed $V_{\text{table}} = 8 \text{ mm/h}$ and for the sawing process performed at a feed rate calculated for each of the 20 blocks

	Magnitude of measurement of surface parameters (μm)				
	TTV	TIR	FPD	WARP	BOW
InSb with constant speed $V_{\text{table}} = 8 \text{ mm/h}$	3.189	2.196	1.409	3.284	0.85
InSb with calculated speed	2.942	2.618	1.378	2.605	0.642

The abbreviations in the table designate: total thickness variation of the wafer (TTV), wafer bow (BOW), wafer warp (WARP), total indicator reading (TIR), maximum distance from the surface to the reference plane (FPD). The values of the measured parameters are given in μm .

The surface parameter measurements demonstrate (Table 4), that the transition from a constant sawing speed to a blockwise wire sawing process, divided into 20 blocks, with optimized feed rates significantly affects the resulting surface quality. According to significance, the obtained surface parameters can be classified as high-priority or low-priority. The prioritization is based on whether specific parameters can be substantially changed in subsequent processing operations (grinding and polishing) or if they are inherently determined during the wire sawing stage and change negligibly at later fabrication steps. Thus, the high-priority parameters include wafer bow (BOW) and wafer warp (WARP). As a result of the experiment, the BOW and WARP

parameters decreased by 25% and 21%, respectively. At the same time, the changes in the remaining parameters were the following: total thickness variation of the wafer (TTV): -8% – total indicator reading (TIR): $+19\%$ – maximum distance from the surface to the reference plane (FPD): -2% .

Conclusions

1. A positive trend in the surface parameter evolution of the sawed wafers has been established. It is shown that the force exerted by the wire on the sample varies with changes in the cut width. Ensuring a uniform force distribution

relative to variations in the sample width favorably affects the surface parameters, which is confirmed by both the analytical calculations and experimental results.

2. The positive trends in the surface parameter evolution of the wafer consists mainly in a substantial change in wafer bow (BOW) and

wafer warp (WARP). In contrast, the change in total thickness variation of the wafer (TTV) and focal plane deviation (FPD) are negligible. The increase in the total indicator reading (TIR) can also be considered insignificant, since this parameter can be corrected during subsequent stages of mechanical processing.

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