BRITTLE FRACTURE AND NEAR-SURFACE DAMAGES IN ELECTRONIC MATERIALS DURING THEIR MULTI-WIRE-SAWING AND LAPPING USING LOOSE ABRASIVE

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ABSTRACT

Multi-wire sawing and double-side lapping using loose abrasive are the initial stages of electronic materials mechanical processing. On the basis of brittle fracture models, the authors have carried out calculations of absolute values of the depth of near-surface damages appearing in silicon, germanium, gallium phosphide, sapphire and lithium niobate wafers during the above mentioned processing procedures fulfillment. Experimental verification of the obtained data of calculation has been done using two materials – silicon and gallium phosphide. Calculated expressions given in this work for determination of the near-surface damages depth, describe near surface damage depth anisotropy in gallium phosphide and sapphire with different orientation of the processed surface: (100) and (111) for gallium phosphide and also for r-, a- and c-planes for sapphire. It has been noted that the accuracy of the near-surface damages depth absolute values prediction according to design formulae given in this work depends on the accuracy of the processed material mechanical properties and on knowledge of hardness of the material, which plays the role of the counter-body (lapping plate, pad or wire). It was proposed to determine the processes material mechanical properties (E, H, K_{Ic}) in one experiment using the method of the depth sensing indentation. An example calculated data use according to near-surface damages depth for correction of the amount of material removed during mechanical processing of gallium phosphide in the course of turning from multi-wire sawing operation to chemico-mechanical polishing, without operation of double-side polishing, has been given.

INTRODUCTION

Multi-wire sawing and double-side lapping using loose abrasive are the initial stages of electronic materials mechanical processing: 1) lithium niobate and quartz used in acoustoelectronics; 2) sapphire and $A^{III}B^{V}$ semiconductor compounds used in optoelectronics; 3) germanium, gallium arsenide and silicon used in microelecronics. During both multi-wire sawing and lapping using loose abrasive, near-surface damaged layer appears, the value of which should be known. Usually, this layer depth is determined experimentally by direct non-destructive methods, e.g. by X-ray method, and by destructive methods, for instance by of angle polished method lap or by the method of axisymmetrical bend [1]. To shorten the period of development and introduction of the new technological processes conformably to the new objects (langasites, gallates, silocon carbide of different polytypes), it is necessary to be able to predict the depth of damages arising from such processing techniques. Earlier [2, 3], the efforts were made to develop the brittle materials abrasive wear models, up to predicting of relative rate of abrasive wear depending on mechanical properties of the processes material (elastic modulus E, hardness H and fracture toughness K_{Ic}).

Recently, the models were developed [4-6], which enabled to calculate absolute values of near-surface damages depth during lapping by loose abrasive, at least for such material most widely used in microelectronics as silicon. The common point in these works is the use of the model of three bodies interaction: material – abrasive – counter-body (lapping pad) [2, 3]. Peculiarity consists in registration of the counter-body (lapping pad) mechanical properties during double-side lapping by loose abrasive and of wire mechanical properties during multi-wire sawing by loose abrasive [4-6].

DESIGN FORMULAE

As the base of calculation, two models of brittle fracture were taken by the authors. In the first model [4], the maximum depth of median and radial cracks penetration in material during effect of acute-angled shape abrasive on the processed material surface was calculated. This value was further taken as the depth of the near-surface damaged layer. It is determined according to the following equation:

$$h_{\text{dam.layer}} = \left[4 \cdot \alpha \cdot \beta \cdot \left(1 + \left[\frac{H}{H'} \right]^{1/2} \right)^{-2} \cdot (H \cdot E)^{1/2} \cdot K_{Ic}^{\;-1} \right]^{2/3} \cdot R_3^{4/3} \qquad (1)$$

where α and β are constants equal to 0.0154 and π, respectively, and E, H, and K_{Ic} are elasticity modulus, hardness and fracture toughness, respectively, H' – counter-body (lapping pad) hardness, R_3 –abrasive particles average radius equal to $d_3/2$. In the second model, the size of plastic deformation zone is determined, at the boundary of which with elastic deformed area, formation and growth of lateral cracks responsible for material removal during the excess of critical force on abrasive particles takes place [7]. This value was further taken as the depth of the near-surface damaged layer. It is determined according to the following equation:

$$h_{\text{dam.layer}} = 2 \cdot \gamma \cdot \left(\frac{E}{H} \right)^{1/2} \tan \Theta \cdot \left(1 + \left[\frac{H}{H'} \right]^{1/2} \right)^{-1} \cdot d_3 \qquad (2)$$

where γ - constant equal to 0.12, tanΘ - sharpness or angularity of abrasive particles. The rest parameters in Equation (2) have the same meaning as in Equation (1). Comparison of calculation data for silicon on two models showed that both the models give the close results in the field of the size of abrasive particles used during silicon wafers double-side lapping by loose abrasive. There was a substantial divergence only for the abrasive particle size > 20 microns. It is explainable, because the depth of median and radial cracks penetration in the processed material includes also the size of plastic deformation area. The model experimental inspection using silicon showed that the cracked layer depth, which is substantively determined by the angle polished method, is a little bit lower than that predicted by the model [5, 6].

Later on, in order to predict the depth of the near-surface damages arising in sapphire with different orientation of the processed surface, in lithium niobate and germanium during their lapping by loose abrasive, and in gallium phosphide during multi-wire sawing and lapping by loose abrasive, calculation was carried out using the model, which gives the maximum estimation of the near-surface depth, i.e. according to Equation (1).

CALCULATION RESULTS

Results of calculation according to Equation (1) are given in Fig. 1 for ceramic materials (lithium niobate, sapphire) and for germanium and gallium phosphide. All calculations were carried out relative to silicon. In order to maintain the parabolic character of the near-surface damages depth dependence in Equation (1) on abrasive grain average size, damages depth in silicon at abrasive grain average size 50 microns was taken as a unit. In Fig. 1 we can see that in lithium niobate, near-surface damages depth during lapping was approximately by 1.65 times higher than in silicon. In germanium, this value was approximately by 1.38 times higher than in silicon. In sapphire, near-surface damages depth during lapping on plane (0001) (c-plane) is 0.50 of the near-surface damages depth in silicon. The same value for r-plane (1,-1,0,2) is 0.71 of the similar value for silicon. And just a little bit lower value 0.68 corresponds to (1,1,-2,0) plane (a-plane).

Similar calculations were carried out for gallium phosphide for multi-wire sawing and lapping by loose abrasive. For more convenient comparison, such calculations were made for silicon. Calculation results are given in Fig. 2. In Fig. 2 one can see that damages depth in gallium phosphide with the cut surface orientation on plane (100) after multi-wire sawing practically coincides with the damages depth in Si (100) after lapping by loose abrasive. Relation between damages depth is 1.01 to 1.0. Damages depth in GaP with the cut surface orientation on plane (111) is 0.91 of the damages depth in Si (100) after lapping by loose abrasive. Anisotropy of damages depth in GaP during multi-wire sawing by loose abrasive for single crystals grown in directions <100> and <111> is evident. In case of cut plane coincidence with plane (111), which is characterized by the highest reticular atomic density compared to plane (100), damages depth is lower, and vice versa.

Damages depth values after multi-wire sawing in GaP, which were experimentally determined by angle polished method, were approximately by 20-40% higher than the predicted ones, and it may be considered as a good result of the forecast.

Naturally, such situation should be reproduced also for the process of lapping by loose abrasive of GaP surface coinciding with planes (100) and (111). As in case of multi-wire sawing by loose abrasive, damages depth during GaP lapping by loose abrasive on plane (100) is higher than for plane (111) in relation 1.39 to 1.27 (or by 1.095 times). Besides, one can see that damages depth after lapping by loose abrasive is in average by 1.385 times higher than after multi-wire sawing by loose abrasive of the same grain size for the processed surface orientation coinciding with both planes (100) and (111).

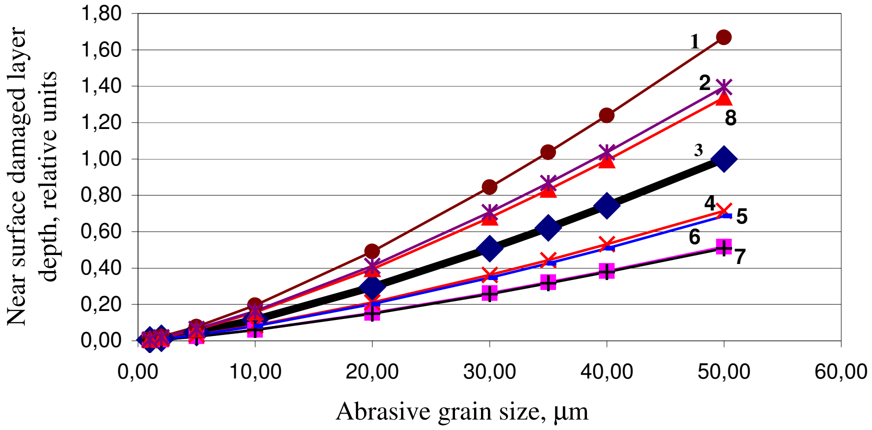

Fig. 1. Near-surface damaged layer depth in ceramic materials versus the grain size during lapping by acute-angled shape loose abrasive.

1 - $LiNbO_3$; 2 - Ge (100); 3 - Si (100); 4 – $(1\bar{1}02)$ Al_2O_3 (r- plane); 5 - $(11\bar{2}0)$ Al_2O_3 (a-plane); 6 - Al_2O_3 (poly crystal); 7 - (0001) Al_2O_3 (c-plane), 8 - GaP (100)

First of all, such difference is stipulated by the counter-body different hardness H’. In case of lapping by loose abrasive, calculation was done for the cast iron lapping pad with pearlite base (H’ = 2 GPa), and for multi-wire sawing by loose abrasive for the steel wire with brass facing, which is the carrier of loose abrasive during multi-wire sawing (H’ = 1 GPa). As it follows from (1) and (2), during processed surface orientation change, E, H, and K_{Ic} change, too. However, they have the lower power dependence compared to power dependence of term $\left[1+\left(\frac{H}{H'}\right)\right]$.

So the forecast accuracy depends on the estimation accuracy of relation H/H’ relation and on the accuracy of determination of the processed material mechanical properties E, H and K_{Ic} and of their change along with orientation, doping type and degree. It is important to determine these values within one experiment, desirably by one method, as it is proposed in [7] where they use the continuous depth sensing indentation method.

Such prediction work importance may be demonstrated using the example of comparison of the depth of damages arising in GaP during processing by loose abrasive (multi-wire sawing and lapping).

As it was already noted, the predicted depth of the near-surface damages during double-side lapping by loose abrasive of the same grain size is by 1.385

times higher than during multi-wire sawing by loose abrasive. At the reached parameters of flatness and micro-roughness of the surface after multi-wire sawing by loose abrasive [8] it became possible for some optoelectronic products to eliminate double-side lapping operation, which increases the depth of the near-surface layer, and to get over to directly to single-side chemico-mechanical polishing, without double-side lapping. As a result, economic indices of GaP (100) polished wafers manufacture can be improved.

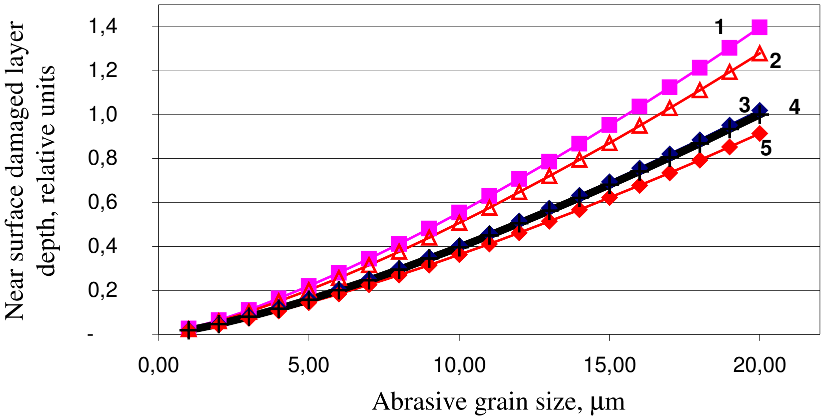

Fig. 2. Near-surface damaged layer depth in GaP (100) and GaP (111) versus the grain size during lapping and multi-wire sawing by acute-angled shape loose abrasive.

1 - GaP (100) lapping; 2 - GaP (111) lapping; 3 - GaP (100) multi-wire sawing; 4 - Si (100) lapping; 5 - GaP (111) multi-wire sawing

CONCLUSION

1. On the basis of the brittle fracture models, calculation of absolute values of near-surface damages arising in Si, Ge, GaP, sapphire, lithium niobate during their processing by loose abrasive has been carried out.
2. Good correspondence of calculated data to experimental ones has been found, at least for two materials, Si and GaP.
3. It has been shown that the proposed calculated data can describe correctly the anisotropy of the near-surface damages depth with different orientation of the processed surface.
4. It has been noted that the accuracy of the near-surface damages depth absolute values prediction according the proposed design formulae depends on the accuracy of determination of the processed material mechanical properties and on knowledge of hardnees of material, which is a counter-body.

5. The example of use of calculated data according the near-surface damages depth has been given for correction of the amount of material removed during GaP wafers processing in the course of getting over from multi-wire sawing directly to chemico-mechanical polishing without double-side lapping operation.

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