Ultra-precision Mechanical Cleavage Technology on Semiconductor Lasers with Broad Area Mirror Facets

Rui Gao[1,2], Chunjin Wang[1*], Qingzheng Zhang[2], Chen Jiang[2], Chi Fai Cheung[1]

1 State Key Laboratory of Ultra-precision Machining Technology, Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong, China
2 College of Mechanical Engineering, University of Shanghai for Science and Technology, 516 Jungong Road, Shanghai, 200093, China
Corresponding Author / Email: chunjin.wang@polyu.edu.hk , TEL: 85234003190, FAX:Nil

KEYWORDS: Ultra-precision machining, Mechanical Cleavage, Semiconductor Lasers, GaAs, Mirror Facet

As a novel technology for high-power semiconductor lasers with broad area mirror facets, mechanical cleavage technology has received extensive attention. The scribing step plays a critical role in the follow-up breaking step to create high-quality cavity mirror. However, there are still a lot of technical gaps to be filled at this stage. In this study, an edge-scribing method was proposed. The scribing energy of the edge-scribing and traditional scribing methods along the [0-1-1] directions were calculated and analyzed regarding energy consumption. The formation of cleaved mirror facets of GaAs-based laser bars was investigated using edge-scribing and traditional scribing methods. The results show that the edge-scribing method can significantly reduce energy consumption during the cleavage of GaAs, and the energy saving ratios exceed 70%. The surface roughness (Ra) of the obtained cleaving mirror facets by the edge-scribing method can achieve 0.43 nm.

NOMENCLATURE

E_G = special grinding energy
P = power rate
Qs = material removal rate
F = applied force,
v_w = wheel speed
h = cutting depth
b = material removal width in the specimen
v = feed speed
Ws = power
l = scribing length
F_n = normal force
F_t = tangential force
θ = tilt angle
E_S = scribing energy
w = kerf width
v_s = scribing speed

1. Introduction

Semiconductor lasers are ubiquitous in today's technology because they are compact, cover a wide range of wavelengths and allow fast electrical modulation [1]. Nowadays, the demand in improving output power of semiconductor laser is a topic of intense interest. To meet this demand, a number of single laser diodes are arranged laterally into a single semiconductor element, which is called laser bar [2]. Meanwhile, a smooth and vertical mirror facet plays a critical role in device reliability for high-power laser bar [3]. Hence, how to fabricate laser bar with broad area and faultless mirror facet in an efficient manner is currently the greatest challenge.

To tackle these issues, the mechanical cleavage technology has been employed in fabricating broad area laser bars in recent years [4]. As shown in Fig. 1, mechanical cleavage consists of two steps: scribing and cleaving [5]. The first step in this process is to scratch on the upper surface of the wafer with a sharp diamond tip, which introduces initial cracks at subsurface for subsequent step. The scribing groove at the edge of wafer is used to induce cleave propagation. Prior to cleaving step, the wafer is flipped and placed on the platform. A cleaving load is applied, which is precisely aligned with respect to the scribing groove. Finally, a smooth cleavage plane is created to serve as mirror facet for the laser bar.

Although, some research has been carried out on the phenomenon of cleavage fracture, there is still very little quantitative analysis of the relationship between scribing and cleaving steps. Furthermore, the current manufacturing industry is continuously striving for low energy consumption, high processing efficiency, and optimal quality during the manufacturing process. As a result, the specific objective of this study is to bridge the existing knowledge gaps and obtain broad area cleavage planes using an efficient mechanical cleavage method. Energy consumption and cleavage plane quality using both the traditional scribing method and edge-scribing method are investigated.

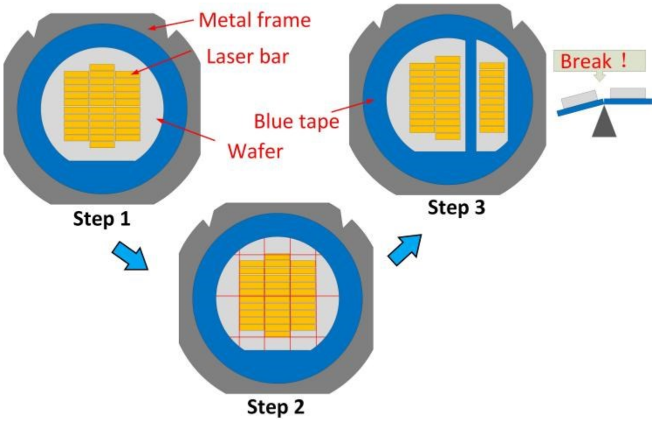

Fig. 1 Flow diagram of mechanical cleavage process.

2. Methodology

2.1 Edge-scribing method

As the first step to cleave wafers, scribing step plays a critical role in creating high-quality cavity mirror. As for the traditional scribing method, the scribing groove is spread along the overall street on the wafer surface as shown in the Fig. 2(a). However, an abundance of initial cracks are generated beneath scribing groove using this method and some of them extend from the top to the bottom of the cleavage plane when the cleavage load is applied. It is very difficult to obtain a relatively high-quality cleavage plane. To handle this problem, a novel approach, called edge-scribing, is proposed as shown in the Fig. 2(b). In this method, scribing groove only exists on one side of wafer, and the appropriate scribing length has a direct impact on the flatness of the cleavage surface. The length of each scribing groove obtained when the stress reaches its peak is the required scribing length in the edge-scribing method. In addition, the plurality of laser bars on a wafer must be cleaved. The innovative approach also has the potential to enhance the efficiency of cleavage processes to satisfy maximization yield production.

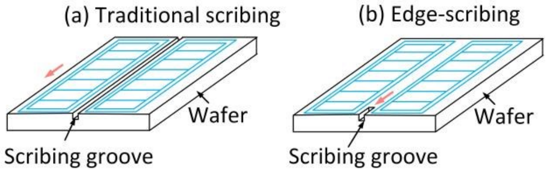

Fig. 2 Scribing method.

2.2 Scribing energy

Compared with numerous process parameters, special grinding energy is a more suitable factor to evaluate the energy consumption during the manufacturing [6], which can be expressed as:

$$E_G = P/Q_s = Fv_w/hbv \qquad (1)$$

Where E_G is the special grinding energy, P is the power rate, Qs is the material removal rate, F is the applied force, v_w is the wheel speed, h is the cutting depth, b is the material removal width in the specimen, and v is the feed speed. As shown in Fig. 2, the tip moves down to the setting cutting depth, which correlates positively with the applied force, and it moves up to the previous height at the end of operation. The scribing step is carried out at a constant applied force. Since the tip does not turn during the scribing operation, the scribing energy can be calculated by the power Ws, which replaces the power rate P. The power Ws is given by:

$$W_s = 2hF_n + lF_t \qquad (2)$$

where Ws is the power, l is the scribing length, F_n is the normal force, and F_t is the tangential force. Due to a tilt angle between the tip and specimen, the normal force and the tangential force can be calculated as:

$$F_n = F\sin\theta, F_t = F\cos\theta \qquad (3)$$

where θ is the tilt angle. The relationship between and the cutting depth h and the tangential force F_n was studied by Zhang et al. [7], as shown in Eq. (4).

$$h = \sqrt[1.87]{F_n/0.3692\times10^{-3}} \qquad (4)$$

By combining Eqs. (2-4), the scribing energy can be given as:

$$E_s = W_s/Q_s = (2hF_n + lF_t)/whv_s \qquad (5)$$

where E_S is the scribing energy, w is the kerf width, and v_s is the scribing speed.

3. Experiment

A series of experiments were performed on n-type GaAs (100) wafer with a size of 30 mm×14 mm×0.35 mm using self-developed machines as shown in Fig. 3. The GaAs (100) surface was precisely polished with chemical mechanical polishing (CMP), and surface roughness of the polished surface was less than 0.5 nm. As for the GaAs (100) surface, the initial cleaving cracks are easier to generate when scribing along the [0-1-1] direction due to low fracture toughness [8] and large interplanar spacing [9]. Hence, GaAs wafers were firstly mounted on the vacuum chuck and scribed along the [0-1-1] direction by a diamond tip as shown in Fig. 3(a-b). The diamond tip is shaped like a rectangular pyramid. Based on our previous works [4], the scribing length is 0.6 mm. The vacuum chuck allows motion along X and Y axes with a resolution of 1μm and rotation around the Z axis with a resolution of 0.02 degree. The load applied for each scratch was modified with a rotating knob. After the scribing step, wafers were turned over and fixed on the platform with a jig as shown in Fig. 3(c). The cleavage platform had two parts that could move along the Y-axis (yellow dotted line) with a resolution of 1μm, and the gap was 0.2 mm in this work. Then, wafers were separated into single laser bar using the ceramic indenter, and cleaving load could be measured by a force sensor with a resolution of 0.5 g. In cleaving operation, the feed speed and cleaving load were 2.5 mm/s and 365 g, respectively. The tip radius of ceramic indenter was approximately 1.5 mm, and the length of ceramic indenter was 80 mm. Since experiments require a high level of precision, an industrial camera was installed on both the scribing machine and cleaving machine for alignment.

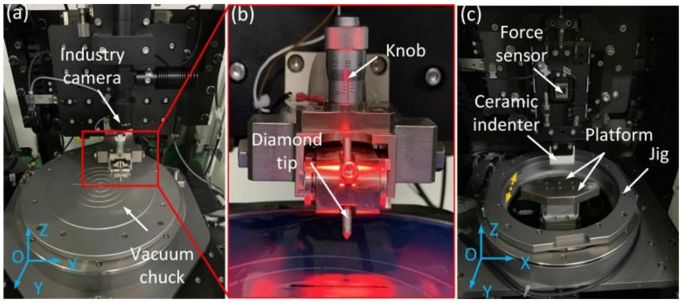

Fig. 3 Setup of (a) scribing machine, (b) magnified view of diamond tip, (c) cleaving machine.

After the experiments, the samples were cleaned again by cleanroom wipers strained with iso-propyl alcohol. For the morphology and maximum damage width measurement, an optical microscope (Keyence, VHX-5000, Japan) and SEM system (Tescan, MIRA3, Czech) were taken.

4. Results

Figure 4(a) provides the calculation data on the scribing energy of [0-1-1] direction. The scribing energy decreases as the scribing speed increases. However, when diverse scribing loads are applied, there is not a significant change in the scribing energy. To be more specific, the scribing energy decreases from approximately 11.133 J/mm^3 to 0.874 J/mm^3 when the scribing speed increases from 5 mm/s to 60 mm/s during traditional scribing, and it declines from approximately 2.368 J/mm^3 to 0.185 J/mm^3 in edge-scratching. In terms of static, compared with traditional scribing, the scribing energy using the edge-scribing method is significantly reduced for [0-1-1] direction, as shown in Fig. 4(b). In addition, the energy saving ratios exceed 70% under all scribing speed conditions.

Figure 5(a) shows the SEM image of (0-1-1) cleavage plane, and the damaged area is 3.16 mm in length (see Fig. 5(d)), which shows a high density of terraces as shown in Fig. 5(c). These results match those observed in earlier studies [10]. In addition, length and surface roughness of undamaged area are 10.84 mm and 0.43 nm, respectively.

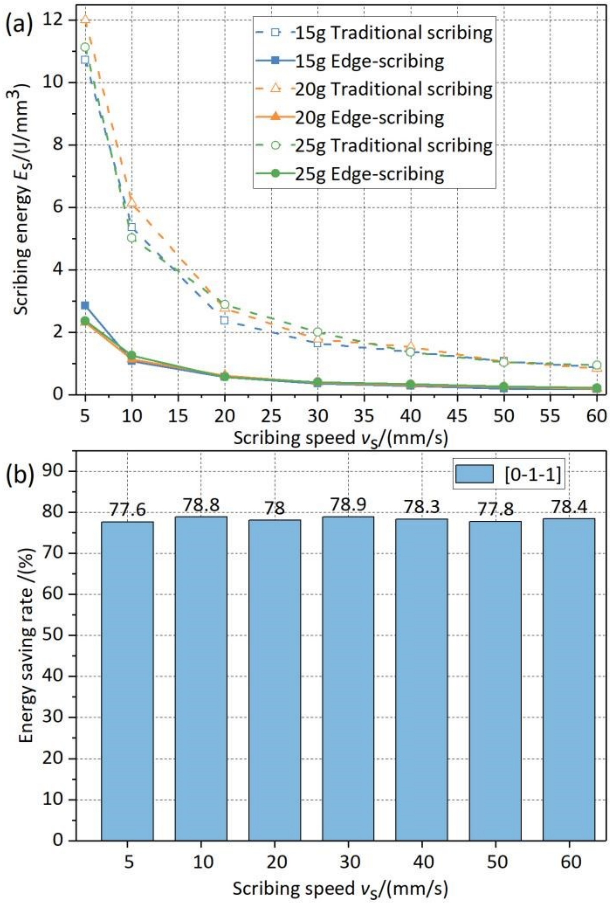

Fig.4 (a) Scribing energy as a function of scratching speed. (b) Energy saving rate as a function of scratching speed

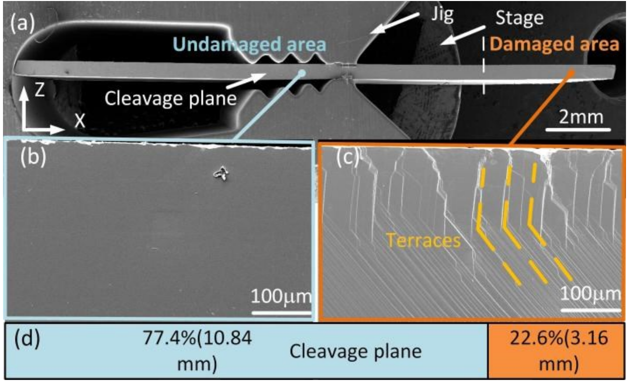

Fig. 5 (a) SEM image of (0-1-1) cleavage plane, (b) magnified view of undamaged area, (c) magnified view of damaged area, (d) schematic draw of cleavage plane.

5. Conclusion

Compared with the traditional scribing method, the use of the edge-scribing method can lead to lower energy consumption in the mechanical cleavage process and has the potential to improve the quality of cleavage planes. By using this method, the achieved undamaged length and surface roughness (Ra) of cleaved planes can achieve 10.84 mm and 0.43 nm, respectively.

ACKNOWLEDGEMENT

The authors would like to express their appreciation for the support of the postdoc matching fund from the Hong Kong Polytechnic University [project code: 1-W308], the State Key Laboratory of Mechanical System and Vibration [Grant no: MSV202315] and the Research and Innovation Office of The Hong Kong Polytechnic University [Project Code: BD9B]. The authors thank the Shanghai Nanpre Mechanics Co.,Ltd. for the support with the experimental instruments.

REFERENCES

1. Paik, E.Y., Zhang, L., Burg, G.W., Gogna, R., Tutuc, E., and Deng, H., “Interlayer exciton laser of extended spatial coherence in atomically thin heterostructures,” Nature., Vol. 576, No. 7785, pp. 80-84, 2020.
2. Jansen, M., Bournes, P., Corvini, F., Fang, F., Finander, M., Hmelar, M., Johnston, T., Jordan, C., Nabiev, R., Nightingale, J., Widman, M., Asonen, H., Aarik, J., Salokatve, A., Nappi, J., and Rakennus, K., “High performance laser diode bars with aluminum-free active regions,” Opt. Express., Vol. 4, No. 1, pp. 3-11, 1999.
3. Krüger, O., Kang, J.H., Spevak, M., Zeimer, U., and Einfeldt, S., “Precision UV laser scribing for cleaving mirror facets of GaN-based laser diodes,” Appl. Phys. A-Mater., Vol. 122, No. 4, pp. 1-7, 2016.
4. Gao, R., Jiang, C., Lang, X.H., Jiang, J.X., and Huang, H.P., “Energy consumption analysis of different scratching methods in GaAs mechanical cleavage processing,” Semicond. Sci. Technol., Vol. 36, pp. 115011, 2021.
5. Wasmer, K., Ballif, C., Pouvreau, C., Schulz, D., and Michler, J., “Dicing of gallium-arsenide high performance laser diodes for industrial applications Part I. Scratching operation,” J. Mater. Process. Tech., Vol. 198, No. 1-3, pp. 114-121, 2008.
6. Jiang, C., Wu, T., Ye, H., Cheng, J.Y., Hao, Y., “Estimation of energy and time savings in optical glass manufacturing when using ultrasonic vibration-assisted grinding,” Int. J. Precis. Eng. Manuf.-Green Tech., Vol. 6, No. 1, pp. 1-9, 2016.
7. Zhang, F.H., Li, C., Meng, B.B., Zhao, H., Liu, Z.D., “Investigation of surface deformation characteristic and removal mechanism for K9 glass based on varied cutting-depth nano-scratch,” Chin. J. Mech. Eng-En., Vol. 52, No. 17, pp. 65-71, 2016.
8. Gao, R., Jiang, C., Dong, K.J., Lang, X.H., Jiang, J.X., Huang, P.H., “Anisotropy mechanical behavior of crystals based on gallium arsenide cleavage processing,” Ceram. Int., Vol. 47, No. 15, pp. 22138-22146, 2021.
9. Gao, R., Jiang, C., Lang, X.H., Zheng, Z.X. Jiang, J.X., Huang, P.H., “Study on mechanical cleavage mechanism of GaAs via anisotropic stress field and experiments,” IEEE. T. Semiconduct. M., Vol. 35, No. 4, pp. 633-640, 2020.
10. Quadbeck, P., Ebert, P., Urban, K., Gebauer, J., and Krause-Rehberg, R., “Effect of dopant atoms on the roughness of III-V semiconductor cleavage surfaces,” Appl. Phys. Lett., Vol. 76, No. 3, pp. 300-302, 2000.