euspen’s 24th International Conference &
Exhibition, Dublin, IE, June 2024
www.euspen.eu

Laser cutting and structuring for processing aluminium nitride chips for optical clocks

Rudolf Meeß, Daniel Albrecht, Carsten Feist

Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany

rudolf.meess@ptb.de

Abstract

Ultrashort-Pulse (USP) lasers are the state-of-the-art tools for the precise processing of sensitive, even coated workpieces. In this study, laser cutting, and laser micro-structuring processes are presented as steps in the manufacturing chain for gold coated aluminium-nitride (AlN) chips. The results of processing with a laser with a pulse width of 20 ns and a wavelength of 355 nm (UV) are compared with the results with a USP laser system with wavelengths of 1030 nm (IR), 515 nm (VIS) and 343 nm (UV). The choice of the laser source and of the process parameters affect the quality of the edges, the amount and mechanism for creating aluminium on processed surfaces and the existence and treatment of melted material and thus the entire manufacturing chain. It is shown that the use of USP exhibits several advantages and thus minimizes the complexity of the manufacturing chain.

Development, Laser beam machining, Manufacturing, Processing

1. Introduction

Optical clocks are operated using trapped ions. A single ion is trapped in ultrahigh vacuum in an oscillating electric field and laser cooled to near zero temperature. External influences are suppressed, and atomic transition frequencies are essentially unperturbed, thus facilitating atomic clocks with relative uncertainties in the range of 10^{-18}.

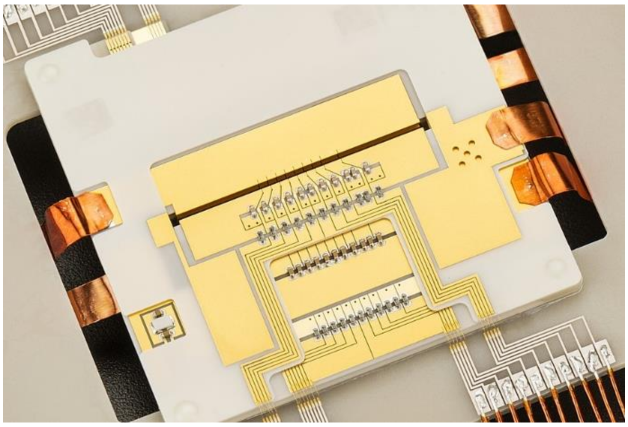


Figure 1. Electrically and thermally connected and assembled ion trap on AlN carrier-frame (Photo: PTB)

At that level of accuracy optical clocks can serve as quantum sensors to measure gravitational potentials with a height resolution in the cm range above the geoid. Fundamental theories such as Einstein´s general relativity theory can be tested in this range [1].

An optical clock for this study is realized by means of a stack of four gold coated and structured aluminium nitride (AlN) chips, which are bonded in a certain distance to each other with spacers at the edges. The AlN chips have a thickness in the range from 120 µm up to 1 mm.

Table 1 Material properties

	AlN	Au
Heat conductivity	175 W/mK	320 W/mK
Thermal expansion	$4.6 \times 10^{-6} K^{-1}$	$14.2 \times 10^{-6} K^{-1}$
Extinction coefficient @ 1030 nm / 515 nm / 343 nm, Absorption depth	Absorption depths 10 nm / 30 nm / 15 nm	6.7038 / 2.0225 / 1.8708[1]
Melting point / decomposition temperature	2.200 °C [4[– 2300 °C [3]	1064.18°C

The gold coating to be structured is applied onto the AlN chips on both sides by means of physical vapour deposition (PVD) and has a thickness of approx. 5 µm. An assembled and connected device in an additional laser-processed AlN frame structure can be seen in Figure 1. The size of the chips is approx. 50 mm × 50 mm.

Laser machining is an appropriate method for structuring a gold plating and for cutting an AlN substrate. The ablation mechanisms of the laser depend on the laser’s wavelength, the optical features of laser beam, and the pulse width regime as well as the optical, thermal, and mechanical properties of the substrate and additional factors (see Figure 2).

Processing aluminium nitride with lasers is unique in that aluminium can potentially form on the surface as a result of thermal decomposition (see table 1). This conductive layer is not intended for the design of the ion traps and must be removed or its formation prevented. This task has been the subject of research for more than 30 years, as this ceramic is used in the manufacture of printed circuit boards.

---

[1] Source: https://refractiveindex.info/?shelf=main&book=Au&page=Johnson

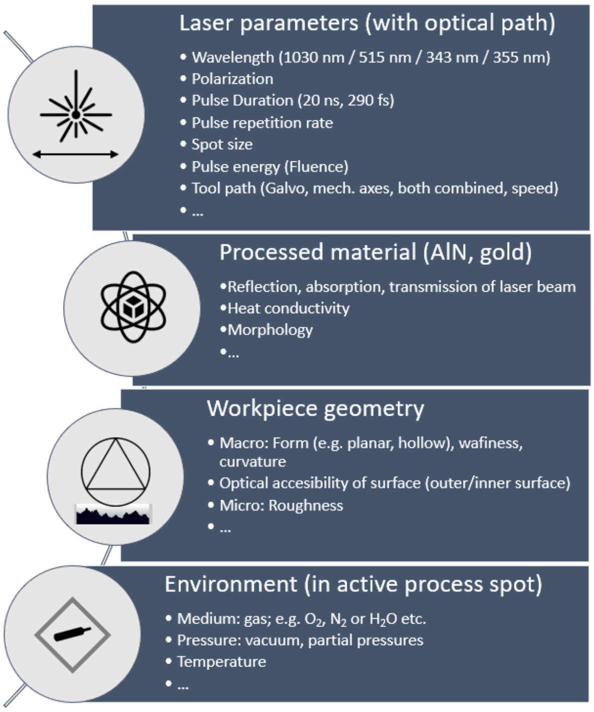


Figure 2. Sketch of influencing variables of laser processing materials

Many theoretical descriptions have been developed to generalize the very complex stages of laser processing. This study cannot claim to analyse all reasonable parameter sets for processing AlN and gold, neither in theory nor in the experiment.

Thus, as a simple and broad approach, in this feasibility study different examples machined with four different beam characteristics are presented and compared.

2. Methods

The thermal conductivity of sintered AlN is about ten times that of alumina, which is the primary reason for its selection here. This high thermal conductivity makes it difficult to machine with a laser because the material can absorb considerable incident energy without melting or vaporizing. Furthermore its transmission is high for the UV wavelength. Process settings that produce good results with alumina, for example, are not suitable for AlN. It is therefore necessary to identify different and appropriate parameters for aluminium nitride.

Processing the gold coating used in some optical clock designs is challenging. A large amount of the gold coated surface must be masked and/or gold must partially be removed after sputtering (see Figure 1). In the uncoated areas, care must be taken to ensure complete electrical insulation over the entire surface in order to avoid electrically undefined charges on metallized islands. For this reason, the surface laser ablation process must also tolerate fluctuations in the thickness of the gold coating sufficiently.

A purpose-built ns laser setup [2] is used in this study to serve as a comparison. The specifications of the Coherent company laser source are shown in table 2, column a. The laser processes are very stable and repeatable. For beam actuation, a galvanometer scanner with F-theta lenses is used. The process chain has remained unchanged over the production of several batches of chips for different generations of ion traps.

Due to the 20 ns pulse length of the AVIA source, thermal influences and debris cannot be avoided during the manufacturing processes. A protective coating is thus used [2] to prevent adhesion of melted material and debris. Furthermore, the coating protects the functional surfaces during the etching process which must be carried out to remove the aluminium surface and oxide layers after laser processing.

Table 2 Laser specifications

	a	b
Laser	Coherent company: AVIA 355-10-20	Light Conversion company: Pharos
Source	3ω Nd:YVO4	Yb:KGW
Wavelength	355 nm	1030 nm / 515 nm / 343 nm
Pulse length	20 ns	290 fs
Pulse energy	Max. 300 µJ	Max. 400 µJ
Repetition rate	10 Hz – 100 kHz	1 kHz – 1 MHz
Beam quality	$M^2 \leq 1,3$ @ TEM_{00}	$M^2 \leq 1,2$ @ TEM_{00}

Aluminium is a product of laser processing AlN [3-6]. Besides the oxides of AlN, aluminium is observed on the surface due to the nanosecond laser induced thermal decomposition of the polycrystalline sintered material at high temperatures [6] in air. The decomposition temperature is approx. 2200°C [4] to 2300°C [3]:

$$AlN_{(solid)} + h\upsilon \rightarrow Al_{(solid)} + N_{(gas)}$$

The aluminium layer and the oxides need to be removed here after the chip and coating have been ablated with the ns UV-laser in air. A standard aluminium etchant for use on silicon devices and other microelectronic applications is used here. This appropriate etching procedure is part of the complex and sensitive manufacturing chain as shown in Figure 3.

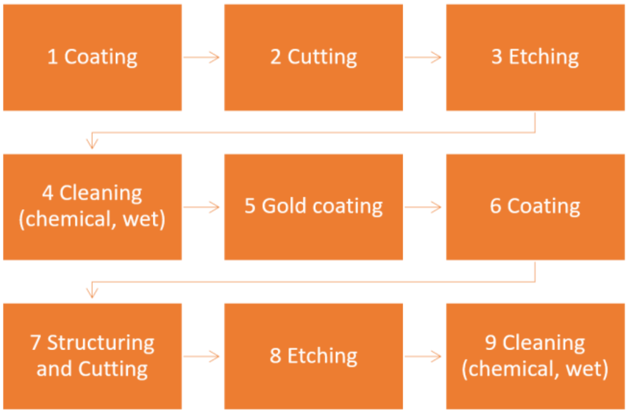


Figure 3. Sketch of the complex process chain with etching processes

Figure 3 does not list the necessary control steps in the process chain. However, the manual operations involved are time consuming. And as the number of necessary processes and control steps increases, the likelihood of damage to the chips and therefore the occurence of rejects – also increases. Therefore, reducing the number of process steps not only saves time in the overall process time per chip and trap, but also valuable working and machining time. This, in turn, decreases the number of semi-finished parts and rejects.

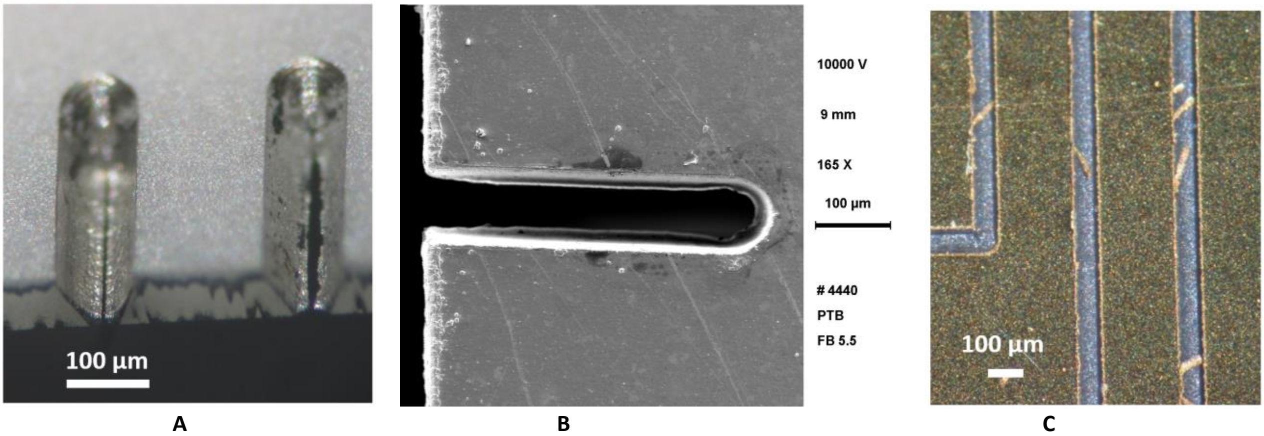


Figure 4. Experimental results of laser processing with 355 nm wavelength and 20 ns pulse length
A: Photo of aluminium layers on AlN surfaces, width of cut on top surface approx. 200 µm; B: Scanning electron microscopy (SEM) image top view of typical cut edge with burr and wavy flanks; C: Photo of typical micro-burr of gold film after simple structuring, gap width of structuring approx. 100 µm

To overcome the nanosecond laser-induced thermal decomposition of the AlN chip, a multi-wavelength USP laser system is applied. The GL.evo laser machining centre of the GFH GmbH company has five axes of motion and is equipped with a Pharos laser system of the Light Conversion company. The specifications of the laser system are shown in table 2 b. The use of USP can reduce the thermal effects in the workpiece.

As stated above, this study cannot claim to be exhaustive as it was not possible to analyse all of the reasonable parameter sets for AlN and gold processing. However, in the context of this feasibility study, meaningful parameter combinations are selected based on experience of working with the laser systems and on approaches that can be found in the literature [5,6]. The burst mode with repetition rates up to the MHz range is not used in this study.

Not all components of the optical path for laser processing are suitable for all wavelength ranges in the GL.evo machine. For this reason, processing with UV is carried out with a fixed optic. In doing so, the possible speed of the beam on the workpiece is reduced, as the mechanical linear axes are used for the relative movement between the two.

The position of the focal plane is a crucial parameter for the quality and efficiency of laser ablation [10]. In this study, the focal plane is selected in such a way that the topography of the cut edge is as homogeneous as possible with the inclined cut surface having a small taper angle. This angle must not be zero due to the constraints of the coating process.

3. Results

Figure 4 shows typical results of processing coated chips with the 20 ns UV laser. Typical aluminium films can be seen on the cut surfaces in the first photo (A). The irregular taper and burr can be seen in photo B. Finally, the burr of the gold can be clearly recognized in the third photo (C). Figure 5 shows a micrograph of a shading on the gold film for marking the chips. No melted edges are visible, even at higher resolution, and due to the very reproducible ablation process, it is possible to partially ablate the 5 µm thick gold film. This avoids isolated islands that could lead to electrostatic charges in the experiment. The lettering is easily recognizable to the naked eye in daylight at any angle of incidence and the numbers are clearly legible.

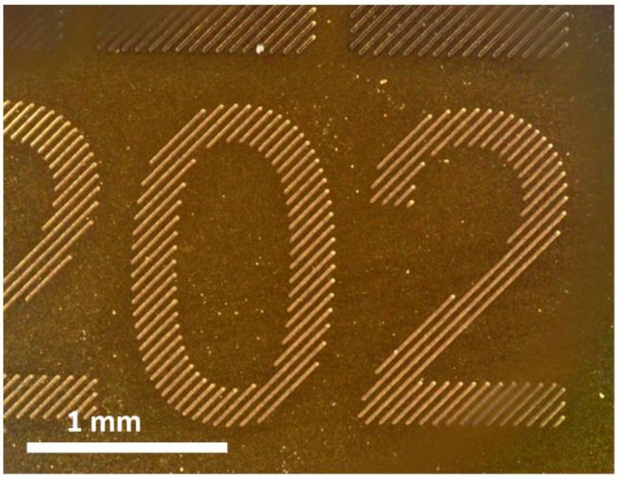


Figure 5. Photo of shading on gold film for marking. The 5 µm thick gold layer is not completely ablated.

With the results of the study, a downsized process chain can be proposed as shown in Figure 6.

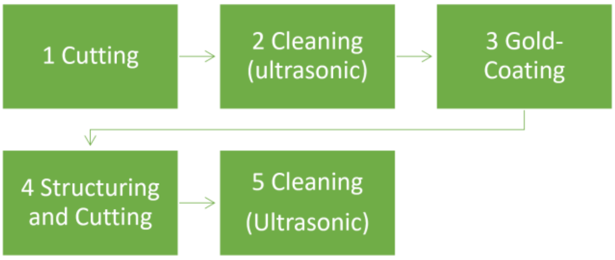
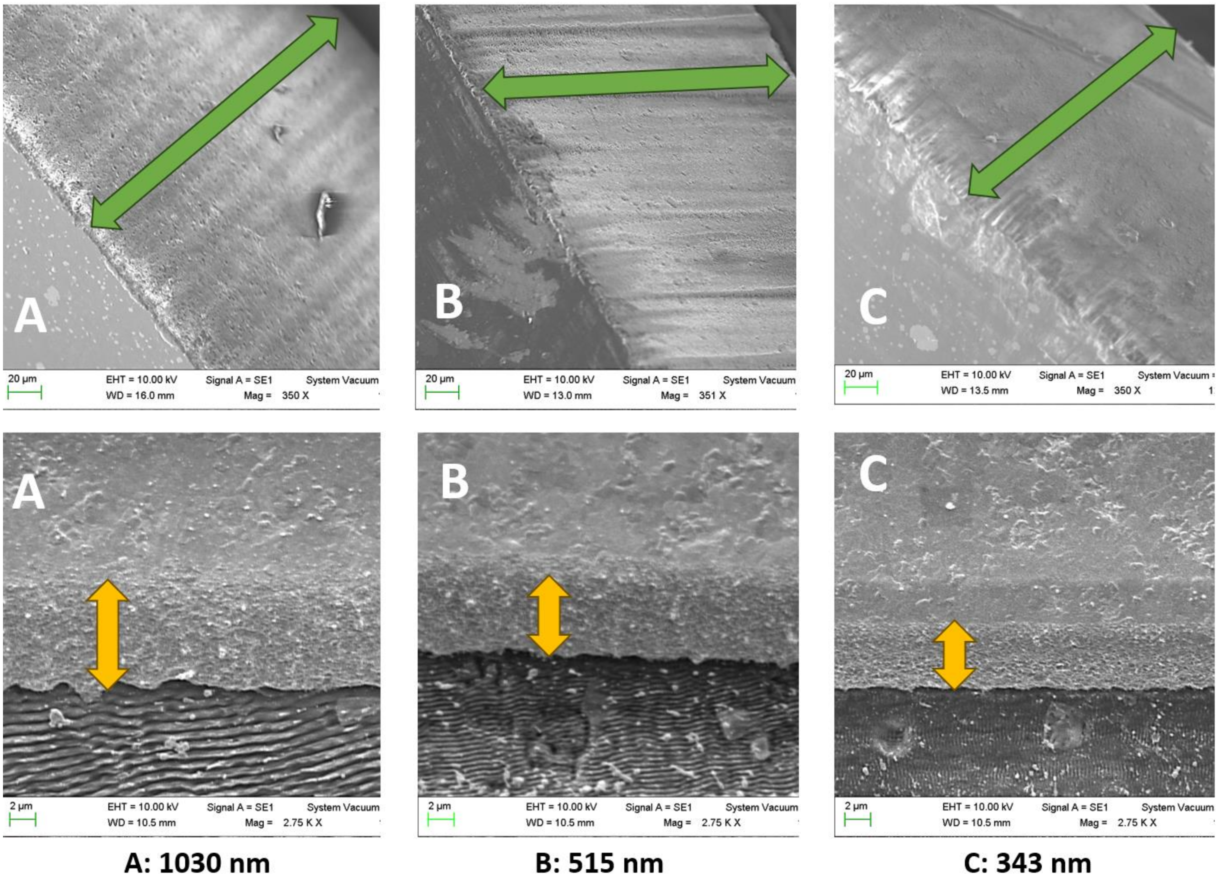


Figure 6. Sketch of novel process chain with reduced number of steps

Wet chemical cleaning steps are no longer necessary, and no etching processes are required. This drastically reduces the number of critical manual operations and the working time per piece.

Figure 7 shows scanning electron microscopy (SEM) images of chips after processing with the USP laser at different wavelengths. The improvements can be clearly seen. No melting of the edges is visible. This means that the thermal effect of the laser radiation is very low.



A: 1030 nm **B: 515 nm** **C: 343 nm**

Figure 7. SEM scans of experimental results of USP laser processing at different wavelengths; A: 1030 nm, B: 515 nm and C: 343 nm. Cut surfaces marked with arrows. AlN (green, AlN top surfaces left) and structured gold coating (yellow, Au coating on upper surfaces)

4. Discussion and Outlook

This feasibility study reports on the laser processing of gold coated AlN chips. The results of processing with light pulses in the UV, VIS, and IR wavelength ranges with a duration of 290 fs at frequencies of 30 kHz to 100 kHz for ablating the gold layer and cutting the ceramic are presented. The results are compared with the results of a laser source with a wavelength of 355 nm and a pulse duration of 20 ns and a repetition rate of 20 kHz. It can be shown that the thermal effects on the gold and the AlN can be significantly reduced when processing with ultrashort pulses. First, the melted edge of the gold layer is missing after ablation with the USP laser. Secondly, no aluminium is visible in the cut of the AlN chips. This indicates that the temperature of approx. 2300°C, which is required for decomposition of aluminium nitride, is not reached during laser cutting.

The decreased influence of thermal effects alone makes it possible to drastically reduce the number of process steps and thus the processing time required to produce of chips for use in optical clocks (see Figure 3 and Figure 6 for comparison).

In a next step, the parameter field will be extended to optimise the process further and shorten the process time. Known engineering optimization techniques may be considered here [8] as well as the use of support through artificial intelligence [9].

Finally, the importance of the binder phase in the sintered AlN during laser processing requires further investigation, especially concerning the high transparency of AlN for the UV wavelength.

References

[1] Herschbach N, Pyka K, Keller J and Mehlstäubler T E 2012 *Appl. Phys. B* **107** 891–906

[2] Meeß R, Löffler F and Hagedorn D 2010 Laser cutting of thin gold foils, in: H. Spaan (Ed.), *Proceedings of the 10th International Conference of the European Society for Precision Engineering and Nanotechnology,* Bd. 2, Bedford: Euspen, 33-36.

[3] Zheng H Y, Phillips H M, Tan J L and Lim G C 1999 Laser-induced conductivity in aluminum nitride *Proc. SPIE 3898, Photonic Systems and Applications in Defense and Manufacturing*,

[4] Kozioł P E, Antończak A J, Szymczyk P, Stępak B and Abramski K M 2013 Conductive aluminum line formation on aluminum nitride surface by infrared nanosecond laser *Applied Surface Science*, **287**, 165-171, ISSN 0169-4332,

[5] Kim S H, Sohn I B and Jeong S 2009 Ablation characteristics of aluminum oxide and nitride ceramics during femtosecond laser micromachining, *Applied Surface Science*, **255**(24) 9717-9720, ISSN 0169-4332.

[6] Hirayama Y, Yabe H and Obara M 2001 Selective ablation of AlN ceramic using femtosecond, nanosecond, and microsecond pulsed laser. *J. Appl. Phys.* 1 **89**(5): 2943–2949.

[7] Loebich O 1972 The optical properties of gold. *Gold Bull* **5**, 2–10

[8] Gadallah M H and Abdu H M 2015 Modeling and optimization of laser cutting operations. *Manufacturing Rev.* **2**(20)

[9] Bakhtiyari A N, Wang Z, Wang L and Zheng H 2021 A review on applications of artificial intelligence in modeling and optimization of laser beam machining, *Optics & Laser Technology* **135** 106721

[10] D. Sola et al *2011*Laser ablation of advanced ceramics and glass-ceramic materials: Reference position dependence *Applied Surface Science **257** 5413–5419*