Single crystal diamond gain mirrors for high performance vertical external cavity surface emitting lasers

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ABSTRACT

We report on the design, fabrication and optical performance of gain mirrors in single crystal diamond substrates for vertical external cavity surface emitting lasers (VECSELs). VECSELs have gained attention recently due to their potential for high emission power in single mode with low beam divergence, yet their maximum output power remains typically limited due to thermal roll-over resulting from insufficient heat dissipation. In order to increase the heat transfer, we exploit the excellent thermal conductivity of single crystal diamond, which is assembled in direct contact with the active structure. The optical cavity is hereby defined by an output coupler and a high reflection grating structure etched into the diamond surface. We here present the design and microfabrication of a diffraction grating that was optimized to reflect light into the 0th order, therefore combining the role of a gain mirror and a heatsink at the same time. Our process involved metal mask deposition onto the diamond surface, e-beam lithography and reactive ion etching. Characterization showed reflection above 95\% at a center wavelength of 1550 nm, potentially allowing the integration of the diamond mirror into a vertical external cavity surface emitting laser.

1. Introduction

Vertical external cavity surface emitting lasers (VECSELs) are semiconductor light sources that provide high optical output power simultaneously with excellent optical beam quality [1]. However, due to limited heat dissipation, VECSELs with emission wavelength above 1200 nm are typically limited in efficiency, with achievable output power typically limited to a few mW [2]. In order to improve their performance, several approaches have been demonstrated previously, including integration of heat spreaders to the gain mirrors [3], employing diamond [4] or silicon carbide [5], or decreasing the thermal resistance of the substrate and distributed Bragg reflector (DBR) by electroplated gold [6,7]. Despite these improvements emission power currently remains limited to 106 W at 1028 nm wavelength [8], 33 W at 1275 nm [9], and 1 W at 1560 nm [10].

We here pursue experimental investigations on the previously proposed double-diamond high-contrast-gratings VECSEL design [11], with the important modification, that the high contrast gratings (HCG) are etched directly into the diamond substrate instead of consisting of a deposited silicon layer, therefore enabling enhanced heat dissipation by the single crystal diamond. Our fabrication approach has been facilitated by the significant advances in fabrication technology of Chemical Vapor Deposition (CVD) single crystal diamond plates in recent years [12–15]. As a result, synthetically grown, high-quality single crystal diamond substrates are commercially available today from various suppliers (e.g. LakeDiamond, Element Six), typically processed by ultra-short pulse laser cutting and mechanical fine polishing [16,17]. Here, we demonstrate a microfabrication approach, based on metal mask deposition onto the diamond surface, e-beam lithography and reactive ion etching for pattern transfer.

In a typical VECSEL configuration, the active structure is attached to a distributed Bragg reflector (DBR) and the latter is in contact with a copper heatsink. Huang et al. presented a configuration in 2007, where the optical cavity was defined between 34 pairs of DBRs as bottom mirror and 4 pairs of DBR and an AlGaAs-based HCG as top mirror [18]. Compared to this design, in our configuration, all the DBRs of the bottom mirror were replaced by a HCG and an output coupler was employed as a top mirror. Furthermore, instead of applying a secondary layer as in [11], our proposed HCG is fabricated directly in the single crystal diamond, therefore integrating also the heatsink into the same...
component. While diffraction gratings in diamond have been demonstrated previously [19–21], we here specifically demonstrate a HCG design that was configured to achieve higher than 95% reflectance at operating wavelength of 1550 nm into the 0th order, which is an essential requirement for integration in VECSEL structures.

2. High contrast grating design

The initial parameters of the HCG were determined based on a previous study [11], and then were optimized by an iterative numerical simulation approach. The parameter search and optimization was performed based on the rigorous coupled wave analysis-based (RCWA) method [22] within a MatLab environment. The structure of the grating can be uniquely described by three variables, the width (B), the pitch (P) and the height of the bars (H). An algorithmic function was constructed that took into consideration the values of these three parameters and calculated the deviation of the 0th order reflection from one. By minimization of this function value, it was possible to find the combination of the parameters that resulted in the highest level of 0th order reflection, when the light approached the grating from the diamond substrate side (Fig. 1). This numerical analysis showed the set of B = 592 nm, P = 1455 nm and H = 419 nm to produce > 99,99% reflection. The result was confirmed by a finite element method (FEM) based simulation, validating the result with an independent numerical simulation method.

Furthermore, FEM based heat-transfer simulations were carried out in order to determine, how the physical dimensions of the diamond plates affect the performance of the VECSEL device. Based on the result of these studies, a $6 \times 6 \times 0.5$ mm$^3$ diamond plate was identified to provide an optimal solution for both heat transfer and assembly.

3. Microfabrication and optical characterization methods

The single crystal diamond plates were obtained in two geometries, $3 \times 3 \times 0.25$ mm (Element Six) and $6 \times 6 \times 0.5$ mm (LakeDiamond). In both cases, the diamond plates were polished as described in our earlier work [23], cleaned with acetone and isopropanol before any further processing in a cleanroom. As a first step, the cleaned diamond surface was coated with a 150 nm thin layer of sputtered titanium (Fig. 2A,F). This metal layer served a dual purpose as it acted as a conductive layer for e-beam lithography and as hard mask for diamond etching. The sputtering was followed by the pattern transfer, for which e-beam lithography was employed to reach a critical dimension of slightly below 600 nm with high fidelity. The diamond plates were spin-coated with hydrogen silsesquioxane (HSQ, Dow Corning XR-1541-006, at 2800 rpm) resulting in a $150 \pm 10$ nm thin layer. The design was then exposed with 3000 μC/cm$^2$ dose. For the development, the diamond plates were placed into 25% tetramethylammonium hydroxide (TMAH) aqueous solution for 4 min.

The quality of the e-beam lithography was investigated by optical microscope and by scanning electron microscope (SEM) qualitatively and by atomic force microscope (AFM) quantitatively (Fig. 2B,G). Using the HSQ as mask, the titanium layer was then etched for 45 s in a STS Multiplex ICP reactive ion etcher using Cl$_2$/BCl$_3$ chemistry. During this process the coil power was set to 800 W, while the forward bias power was 150 W (Fig. 2C,H). After opening the metal mask, the diamond could be etched directly, as we used the same tool for the latter etch, however, in our protocol, the diamond plates were removed from the etcher, washed in deionized water, inspected by SEM and then placed back into the same etcher. In order to etch the diamond, the configuration was changed to 400 W coil power, 200 W forward bias power and solely O$_2$ was employed for the plasma to generate the reactive ions. This setup allowed a diamond etch rate of 90–100 nm/min, depending on the feature dimensions, a phenomenon well documented in literature for dry etching processes as Aspect Ratio Dependent Etching (ARDE) [24,25] (Fig. 2D,I).

The last step of the fabrication process consisted in the removal of the remaining mask materials from the surface by placing the diamond plates into 49% Hydrofluoric acid (HF) solution for 5 min. The fabricated gratings were subsequently measured by SEM and AFM to confirm the geometrical shapes and dimensions (Fig. 2E,J).

Reflection measurements were conducted on an optical bench with the following setup (Fig. 3). A tunable laser (Agilent 8164A) was connected to a circulator (Thorlabs 6015-3-APC) that conducted the light to the sample through a gradient-index (GRIN) fiber collimator with anti-reflection coating (Thorlabs 50-1550A-APC). The sample was placed on a stage with two-axis tilt control and two-axis lateral translation control, while the working distance of the collimator was respected. The reflected light was collected by the fiber collimator and reached a power meter (HP 81531A) through the same circulator as detailed earlier. In order to calculate the power loss of our setup, a reference sample was always measured before the experiments. This
A gold-coated (100 nm film) silicon wafer, for which an absolute reflectance of 98.66% at 1550 nm wavelength was assumed, based on literature data [26].

4. Results

The fabricated single crystal diamond HCGs were analyzed both qualitatively and quantitatively (Fig. 4.A). The SEM images showed well-defined structures of the extruded bars with smooth and near-vertical sidewalls.

In particular, as a result of the optimized etch process, we did not observe any micromasking in the trenches between the bars, which is a common challenge in nanostructuring of diamond [27](Fig. 4.B). In order to determine the exact dimensions of the three main design parameters, the HCG was measured quantitatively by AFM (Fig. 4.C). The target dimensions are reported with potential fabrication tolerances that would still allow the 0th order reflection to be higher than 99% and the measurement values are averages with their error bars as calculated standard deviation (for a sample number n > 15). Although the fabricated bar width turned out slightly smaller than the target, it remained within the tolerance region, while pitch and height deviated only a couple of nanometers from the target dimensions.

The SEM recordings reveal contrast differences on the top of the extruded bars (Fig. 4.B and Fig. 5.A). AFM measurements of the top of the bars, the trenches and the diamond surface outside the grating area are reported in Fig. 5.B as averages over n = 15 measurements with error bars as calculated standard deviation (n = 15). No significant difference between the three investigated areas was found. Furthermore, we could not observe any of the contrast difference-generated shapes on the AFM images; therefore, we concluded that the nature of the observed contrast variations are most likely caused by a surface modification rather than residues e.g. from the masking material.

Optical performance was experimentally assessed employing the characterization setup described in the methods section. The spectral response for the wavelength range 1550 ± 3 nm was recorded with 0.02 nm increment both for the gold reference and for the HCG. As the grating was designed to work with TE polarized light, the polarization controller was set accordingly to maximize the optical response, as well as the tilted stage that was adjusted to provide perpendicular surface relative to the GRIN fiber collimator. Since the reflection of the gold surface is independent from the polarization, these adjustments did not influence the reference reflectivity. The results are summarized in Fig. 6. Our gold reference provided 98.66% reflection, while the fabricated HCG reached 95.85% at 1550 nm wavelength. The periodic variation in recorded intensity, is resulting from the Fabry–Pérot cavity between the diamond plate top and bottom surfaces (see Appendix A).

5. Discussion and conclusion

The reflectivity of the single crystal high contrast grating was experimentally determined to be 95.85% at 1550 nm, which is ~3%
when the dispersion is negligible, i.e. \( \frac{\Delta n}{n} = 0 \), which was found in this case as \( \approx -0.00879 \frac{\text{nm}}{\mu\text{m}} \). Rearranging the equation yields:

\[
L = \frac{c}{n(\lambda)\Delta\nu} = \frac{c}{n(\lambda)\frac{\lambda_2 - \lambda_1}{\lambda_1}} = 456.223 \mu\text{m}
\]

when \( |\lambda_1 - \lambda_2| \approx 2.2 \text{ nm} \), which was found for several measurements. For a standing wave cavity, the physical length is half of \( L \), which translates to 228.112 \( \mu\text{m} \). This was in good correspondence with the datasheet of the diamond plate, which stated that the plate thickness is 250 ± 50 \( \mu\text{m} \).

In summary, we have presented an advanced diamond microfabrication process enabling structuring of single crystal diamond surfaces with pattern dimensions of 100 nm–1500 nm, with precision of ~10 nm. Based on this process, we have experimentally demonstrated a high contrast grating etched into a single crystal diamond yielding reflectivity exceeding 95% at a wavelength of 1550 nm. Such high contrast gratings in diamond are potentially excellent candidates for integration in VECSEL structures to enable high power lasing structures by exploiting the high thermal conductivity of single crystal diamond. This technique can further be extended to create various mechanical and optical components, such as lenses, gratings, or diffractive optical elements.

Declaration of competing interest

LakeDiamond SA is interested in the commercial exploitation of the device described in the manuscript. All other authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

The free spectral range calculation for the Fabry-Pérot cavity was started from the equation \( \Delta\nu \approx \frac{c}{n(\lambda)\Delta\rho} \) when the dispersion is negligible, i.e.

\[
\frac{\Delta n}{n} = 0, \quad \text{which was found in this case as} \quad \approx -0.00879 \frac{\text{nm}}{\mu\text{m}}.
\]

Rearranging the equation yields:

\[
L = \frac{c}{n(\lambda)\Delta\nu} = \frac{c}{n(\lambda)\frac{\lambda_2 - \lambda_1}{\lambda_1}} = 456.223 \mu\text{m}
\]

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