High numerical aperture silicon collimating lens for mid-infrared quantum cascade lasers manufactured using wafer-level techniques.

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ABSTRACT

We present an aspheric collimating lens for mid-infrared (4–14 μm) quantum cascade lasers. The lenses were etched into silicon by an inductively coupled plasma reactive ion etching system on wafer level. The high refractive index of silicon reduces the height of the lens profile resulting in a simple element working at high numerical aperture (up to 0.82). Wafer level processes enable the fabrication of about 5000 lenses in parallel. Such cost-effective collimating lens is a step towards the adoption of quantum cascade lasers for all its potential applications.

Keywords: Optical collimation, mid-infrared micro-optics, quantum cascade laser, reactive ion etching, mass production

1. INTRODUCTION

All chemical species including organic compounds exhibit resonances with their fundamental ro-vibrational modes at frequencies in the mid-infrared spectral range. This range is of great interest for chemical sensing for the environment or for health.[1] The mid-infrared technology include small and highly tunable laser sources: the quantum cascade lasers.[2] This technology progressed rapidly[3] and is now ready for industrial application. Its avenues to the technological applications are, however, difficult unless standard optical elements such as collimating lenses, beam-splitters, polarisers, anti-reflection coatings, waveguides are available.

The mid-infrared light requires the use of special materials and sometimes of different approaches compared to the ones used for the visible or near-infrared light. There are several producers of mid-infrared optics. The fabrication methods they use and the material they propose result typically in expensive optical elements limiting the proliferation of the mid-infrared technologies.

In this contribution, we present the realisation of a collimating lens adapted to the emission pattern of typical quantum cascade lasers. It was required by our industrial partner that the design matches the limits of their proprietary fabrication process in order to facilitate mass production of the lens.

2. CONSTRAINTS AND OPTICAL DESIGN

Using a goniometric mount, we measured the intensity profile of several beams from quantum cascade lasers. Three typical beams are shown in Fig. 1. A plot of the intensity cross section of the beam in Fig. 1 (A) is shown in Fig. 2. The divergence of the measured beams are within ±60°, an angle corresponding to a numerical aperture (NA) of 0.87 in air. Most beams, however, have a divergence within ±50°, corresponding to a NA of 0.77 in air.

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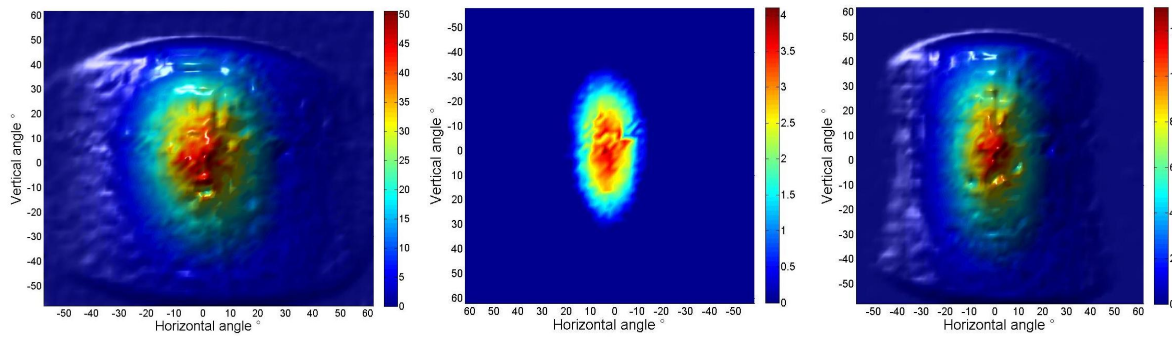


(a) (b) (c)

Figure 1. (a-c) Measured intensity profile of three laser beams from quantum cascade lasers.

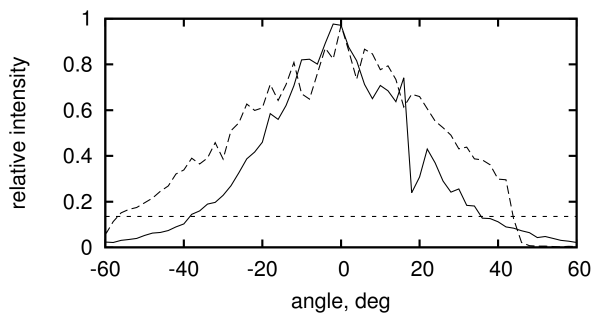


Figure 2. Intensity cross-sections along the two axis of the beam profile shown in Fig. 1 (a). The horizontal dashed-line at 0.135 corresponds to the intensity level of the waist of a Gaussian beam.

We use an inductively coupled plasma reactive ion etching (ICP-RIE) system to etch the lenses on silicon wafer. The previous limits of this technology at our fabrication laboratory (SUSS MicroOptics) were a lens diameter of 1.0 mm and an apex height of 0.1 mm. A surface profile with a root mean square (RMS) error 300 nm is commonly achieved. For this project, the lenses diameter was extended to 2.0 mm and the apex height to 0.2 mm. The goal is to achieve a collimation with a residual semi-divergence of 10 arcmin, i.e., a beam diameter of 6 mm at 1 m.

This goal can not be achieved for the long wavelengths as diffraction alone set an higher divergence. The wavelength limit λ_l can be estimated from the divergence of a Gaussian beam

$$\theta = \frac{1}{\pi}\frac{\lambda}{w_0}, \tag{1}$$

where θ is the semi-angle of divergence, λ the wavelength, and w_0 the radius of the beam waist (86% of the beam energy is within this radius). Using $w_0 = 1\,\mathrm{mm}$ and $\theta = 0.003\,\mathrm{rad}$, the wavelength limit is $\lambda_\mathrm{l} = 9.4\,\mu\mathrm{m}$. In practice, the beams are not perfectly Gaussian ($M^2 > 1$) and the lens truncates the beams. Therefore, the limiting wavelength is shorter than $9.4\,\mu$m.

Due to the high refractive index of silicon in the mid-infrared—3.417–3.425 for wavelengths between 4 and $11\,\mu$m[4,5]—the optical design is greatly simplified compared to a similar lens made of material with refractive index below 2. Both the optical aberrations and the curvature of the lens profile are greatly reduced.

The element considered is a plano-convex asphere of the form

$$z = \frac{cr^2}{1+\sqrt{1-(1+k)c^2r^2}}, \tag{2}$$

where z is the surface height, c is the curvature—the reciprocal of the radius of curvature ($1/R$),—and r the distance from the optical axis. In Fig. 3 the schematic drawing of the designed lens is shown. It benefits from the

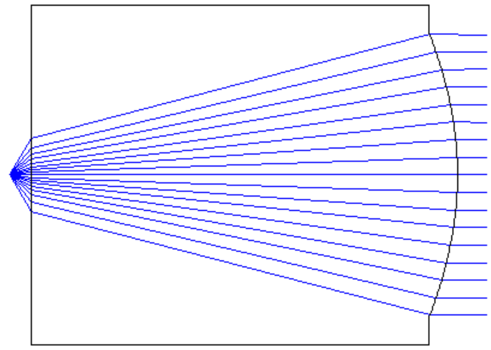


Figure 3. Schematic drawing of the collimating lens with a thickness of 3.0 mm and an aperture of 2.0 mm. The design benefit from the high refractive index of silicon.

reduced beam divergence within the lens high refractive index medium. A thick lens has two advantages over a thin lens. The first advantage is a reduced power, and therefore, a reduced sensitivity to fabrication errors and misalignment. The second advantage is a reduction of the total spherical aberration. The spherical aberration introduced by the thick lens substrate partly compensates the spherical aberration introduced by the curved surface.[6] The remaining aberration is minimised by an asphericity of the curved surface.

We set the lens thickness at 3.0 mm and obtained a working distance of 0.15 mm. Then the lens was optimised by varying R and k using Zemax (Optima Research, UK) for the wavelengths of 4, 6, 8, and 11 μm. We obtained $R = -2.450$ mm and $k = -1.742$. These values did not change significantly when the optimisation was performed for a single wavelength. The height of the lens apex is 0.198 mm. A plot of the lens profile is shown in Fig. 4 together with a plot of a sphere with $R = -2.450$ mm.

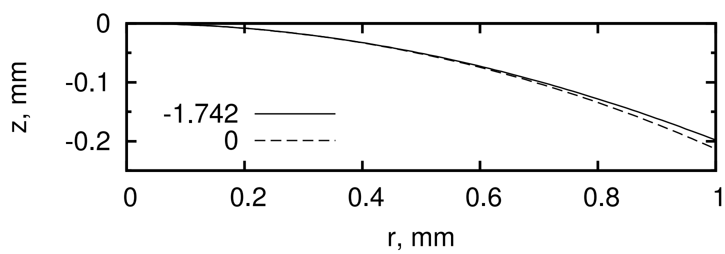


Figure 4. Plot of the lens profiles; the continuous line shows the aspheric profile with $k = -1.742$ and the dashed line shows the spherical profile $k = 0$. A minute aspheric correction is applied.

The ray fan plot for a wavelength of 6 μm is shown in Fig. 5. The horizontal axis shows the ray position in the pupil ranging from -1 to 1 mm. A value of ± 1 mm corresponding to a NA of 0.87. The vertical axis shows the ray divergence. It ranges from -20 to 20 mrad. One milliradian corresponds to a displacement of 1 mm at 1 m. The ray divergence is within ± 4.2 mrad over 91% of the aperture or up to a NA of 0.82. This aperture accepts the light with a divergence angle up to 55°, a value adequate for most lasers. The shape of the ray-fan plot reveals the amount of uncorrected fifth-order spherical aberration.

The addition of higher-order aspheric terms to Eq. (2) would slightly improve the performance of the lens. However, the surface height difference between both designs is too small to be reliably fabricated with respect to the fabrication tolerances.

3. LARGE SCALE FABRICATION PROCESS

For the manufacturing of the micro-optics we used 200 mm wafers which are probably the best choice for a competitive fabrication process. The first step in the fabrication process is the uniform resist coating of the wafer. As the uniformity of the resist layer is directly related to the uniformity of the microlenses after melting

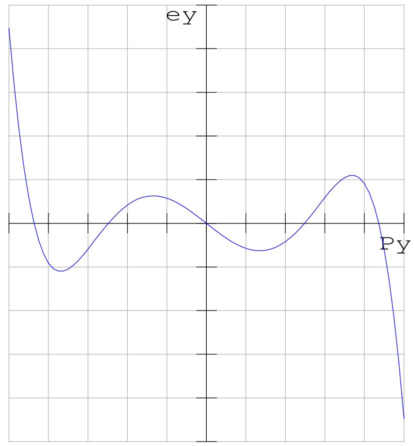


Figure 5. Ray-fan plot for a wavelength of 6 μm. The horizontal axis is the ray position in the pupil. It ranges from -1 to 1 mm. The full aperture corresponds to an NA of 0.87. The vertical axis is the ray divergence in milliradian. It ranges from -20 to 20 mrad.

a non-contact measurement tool (reflected light spectroscopy) is used for controlling the coating process. For the high numerical silicon lenses the resist thickness was close to 90 μm and we achieved a uniformity of 1.2% (RMS). Figure 6 shows the complete manufacturing process. After resist coating of the wafer the lithography process (exposure and wet chemical development) provides small resist cylinders. A subsequent resist melting process delivers the resist lenses.[7,8]

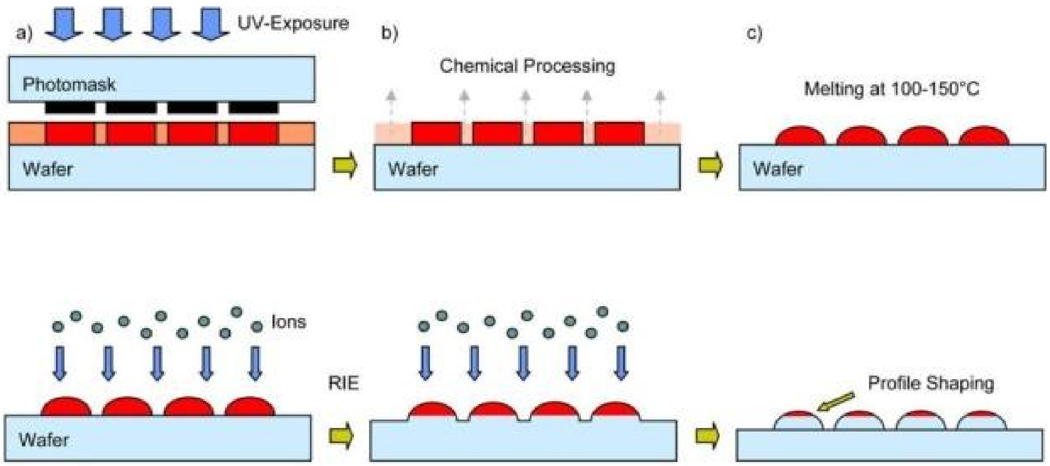
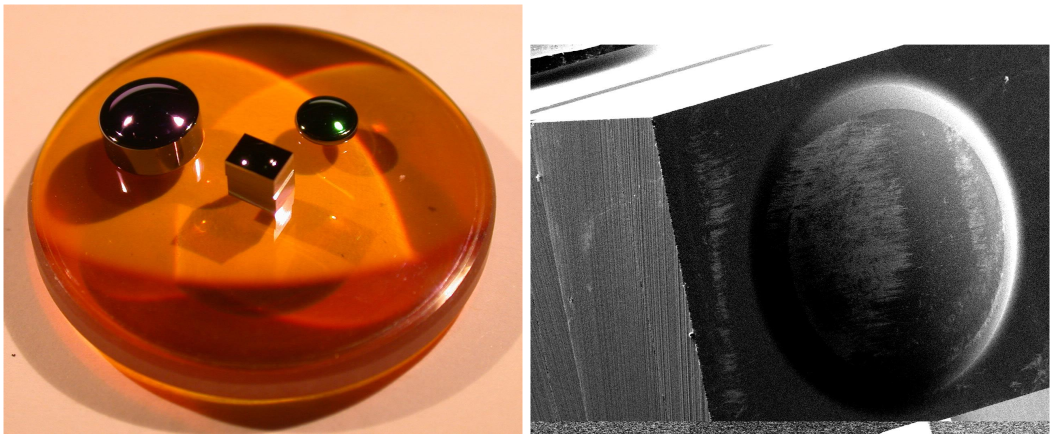


Figure 6. Fabrication of the silicon microlenses.

Melted resist lenses are usually very close to a spherical lens profile with a conic around $k \approx 0$ after melting because of surface tension. The transfer of the melted resist lens by an inductively coupled plasma reactive ion etching (ICP-RIE) system allows changing this lens profile to an aspheric lens shape. This is done by varying the mixture of the etch gases and oxygen during the etch process. If the etch rate for resist is higher than for the wafer bulk material, the resulting lens profile will be flatter than the resist lens profile. In our case the resist etch rate was lower as the silicon etch rate. Like this we could fabricate silicon lenses with a lens height of nearly 200 μm out of 150 μm high resist lenses in a 12-hour etch process.

4. MECHANICAL AND OPTICAL CHARACTERISATIONS

Collimating lens for mid-infrared light beams are shown in Fig. 7 (a). A commercially available standard polished ZnSe lens with a diameter of 25.4 mm supports three lenses. The rectangular lens is the one presented in this contribution. Its dimensions are 3.2 mm × 2.2 mm and a height of 3.0 mm. Next to our lens lie two commercialy available molded lenses with a diameter of 6.2 and 3.8 mm, respectively (Lightpath, Inc.). An electron-micrograph of our lens is shown in Fig. 7 (b).



(a) (b)

Figure 7. (a) Image of collimating lenses for the mid-infrared wavelength. A standard polished ZnSe lens with a diameter of 25.4 mm, two moulded lenses with diameter of 6.2 and 3.8 mm, and the lens presented in this contribution with a rectangular shape of 3.2 mm × 2.2 mm and a height of 3.0 mm. (b) Electron micrograph view of our lens.

The lens profile was measured using a stylus profilometer up to a radius of 0.75 mm. A plot of the profile is shown in Fig. 8 (a). The difference of this profile with the design is shown in Fig. 8 (b). A fit of the measured height returned a radius of curvature of 2.525 mm and a conic constant of −2.0. A difference of 3% and 14% for the radius of curvature and the conic constant, respectively. The RMS error is 450 nm.

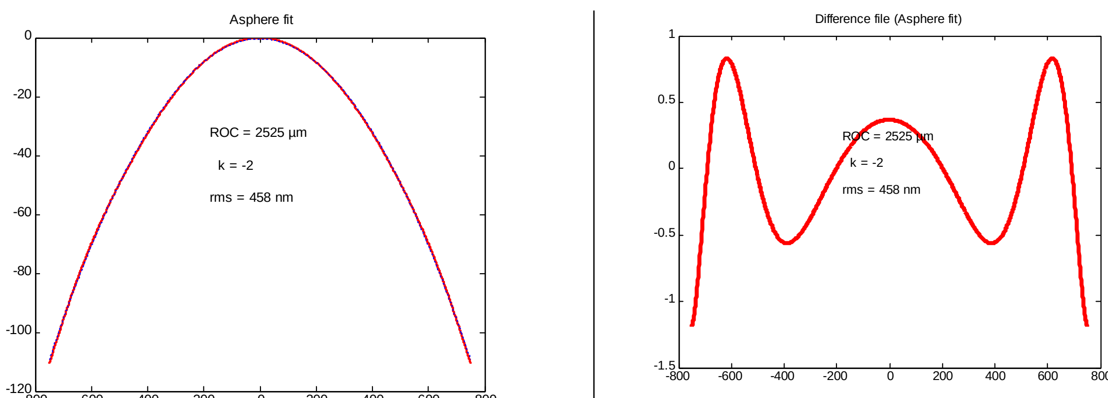


Figure 8. (a) Measured lens surface profile; (b) Difference with the designed profile, all units in micrometer.

The light from a quantum cascade laser was collimated using the new lens. This laser emits at a wavelength of 11 μm with the divergence shown in Fig. 1 (a). The beam divergence was measured in a x-y scanner at different distances from the lens. The full width at half maximum of the beam for the fast and the slow axis is shown in Fig. 9. For this particular laser, the beam diameter is approximately 6 mm at a distance of 0.9 m.

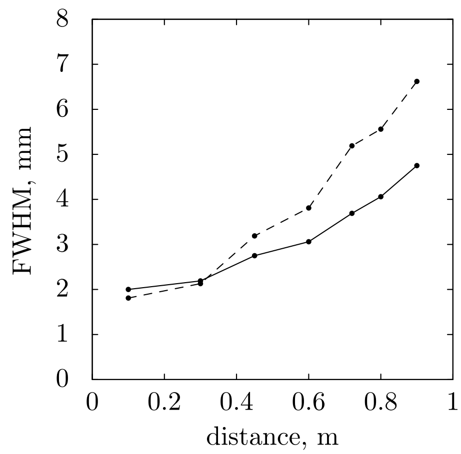


Figure 9. Measured beam full width at half maximum (FWHM) versus propagation distance.

5. CONCLUSION

We have designed, realised, and characterised a simple plano-convex asphere for the collimation of quantum cascade laser beams using inductively coupled plasma reactive ion etching (ICP-RIE) in silicon. The beam collimation is within ± 4.2 mrad up to a NA of 0.82 corresponding to a divergence angle of $\pm 55°$ for wavelength shorter than approximately $9\,\mu$m. For longer wavelengths, the beam divergence is dominated by diffraction.

The size of the lens was a challenge for the technology. Both the diameter and the apex height of the realised lens exceeds the initial limits of the process by 100%. The measured profile closely match the designed profile within a diameter of 1.5 mm with a RMS error of 450 nm. The lenses were fabricated on wafer with a diameter of 200 mm, using processes suitable for mass production.

The optical performance of the lens was measured for a laser beam. The residual divergence is within 7 mrad, a value close to the designed goal. An anti-reflection layer for this lens is being developed.

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