Binary subwavelength structures that act simultaneously as antireflective and diffractive structure for the mid-infrared wavelength range

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Summary

We present a single-layer of binary subwavelength structures designed to reduce Fresnel reflections at an interface while providing an efficient diffractive function.

Introduction

While laser sources and detectors are increasingly available for the mid-infrared (MIR) wavelength range (3-20 µm), there is still a lack of passive optical components. Silicon and germanium are materials of choice for such components. However, their high refractive indices induces high Fresnel losses at the interface. In this presentation, we propose a design method for combining anti-reflective and diffractive functions for an optical element made of silicon. These types of structures have recently been renamed as metasurfaces.

Design of binary structures with effective indices

Using periodic subwavelength structures of various sizes allows the effective index of the medium to be tailored to a desired value. The effective refractive index is mainly determined by the volume ratio of the substrate and the surrounding medium [1]. The allowed effective index range is delimited by the index of the surrouding medium and of the substrate.

We propose a binary grating design in which the phase difference is not coded by the depth of the structures, but rather determined by the effective index difference between subwavelength structures of the same depth but different fill factors. For simplification purposes, the subwavelength patterned region is seen as a uniform layer with an effective refractive index and a thickness equal to the depth of the structures.

In this case and for a binary grating, the phase difference between two different regions should be π. The depth of the structures and the effective refractive indices are therefore tied by the following equation

$$d\Delta n = \frac{\lambda}{2} \tag{1}$$

where d is the depth of the structures, Δn the difference of effective refractive indices and λ the wavelength of the incident light.

Fabrication

Thanks to the binary design, the structures can be fabricated with a single etching step. The process steps are the following: the patterning of the structures is made using a low voltage e-beam writer; a 270 nm thick layer of ZEP 520A resist is exposed with a varying dose between 36 and 39 µC/cm^2; after development of the exposed areas, the substrate is cleaned with an O_2 plasma; a 75 nm thick mask layer of Al_2O_3 is then deposited on the substrate by e-beam evaporation; the resist and unwanted Al_2O_3 is removed by a lift-off process; the substrate is finally dry etched using a plasma of C_3F_8 and SF_6 gases.

Figure 1 presents the structures fabricated. It shows an SEM picture of silicon pillars of 1.25 and 1.8 µm diameter arranged in a 2 dimensionnal array with a 2 µm pitch. Figure 2 presents a side view of the same silicon pillars. The pillars height is 3.46 µm.

Results

Dammann gratings are being used for fabrication and characterization of the optical performance of the binary subwavelength elements. These gratings produce a pattern with homogeneous diffraction efficiencies for a desired number of diffraction orders [2]. The performance of the element is measured both in terms of facet reflectivity and uniformity of the diffractive pattern. Using rigorous coupled wave analysis (RCWA)[3], we compare the performance of a binary Dammann grating and a subwavelength-patterned binary Dammann grating, both realized in silicon.

For a three beam Dammann grating illuminated by light at 7.784 µm wavelength and using a silicon substrate with a refractive index of 3.4190 [4], the reflectivity drops from 29% to 7.5%. The beam pattern uniformity stays stable, increasing only from 0.1% to 0.5%. The fabricated structures will be characterized using a tunable quantum cascade laser.

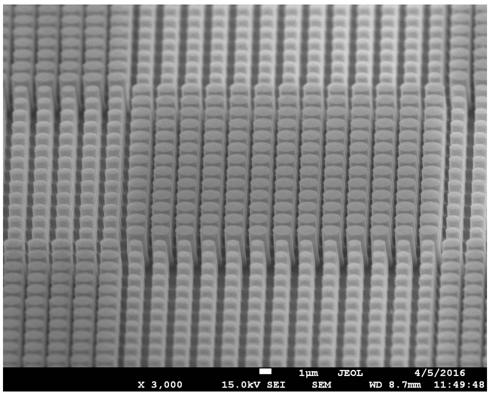

Fig 1: SEM picure of silicon pillars forming a 2D Dammann grating

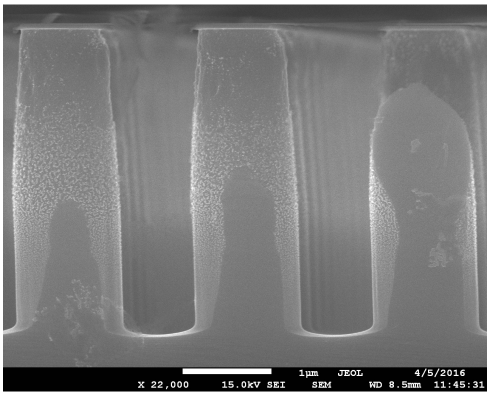

Fig 2: SEM side view of silicon micropillars of 3.46 µm height

Discussion

The proposed design greatly reduces Fresnel reflections at the interface for silicon elements. The same principle can be applied to other high refractive index materials. Subwavelength-patterned structures provide a fourfold reduction in facet reflectivity compared to a normal Dammann design in silicon. The uniformity of the diffraction pattern is slightly worse than the standard design but is still well within acceptable values.

Conclusions

We proposed a design method for binary gratings using subwavelength patterned areas. The designed structures reduce the Fresnel reflection and provide similar optical performance compared to standard binary gratings.

References

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