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APPLICATION NOTE

SILICON METALENS WITH SUBWAVELENGTH RESOLUTION FOR HIGH-PERFORMANCE FLAT OPTICS

by

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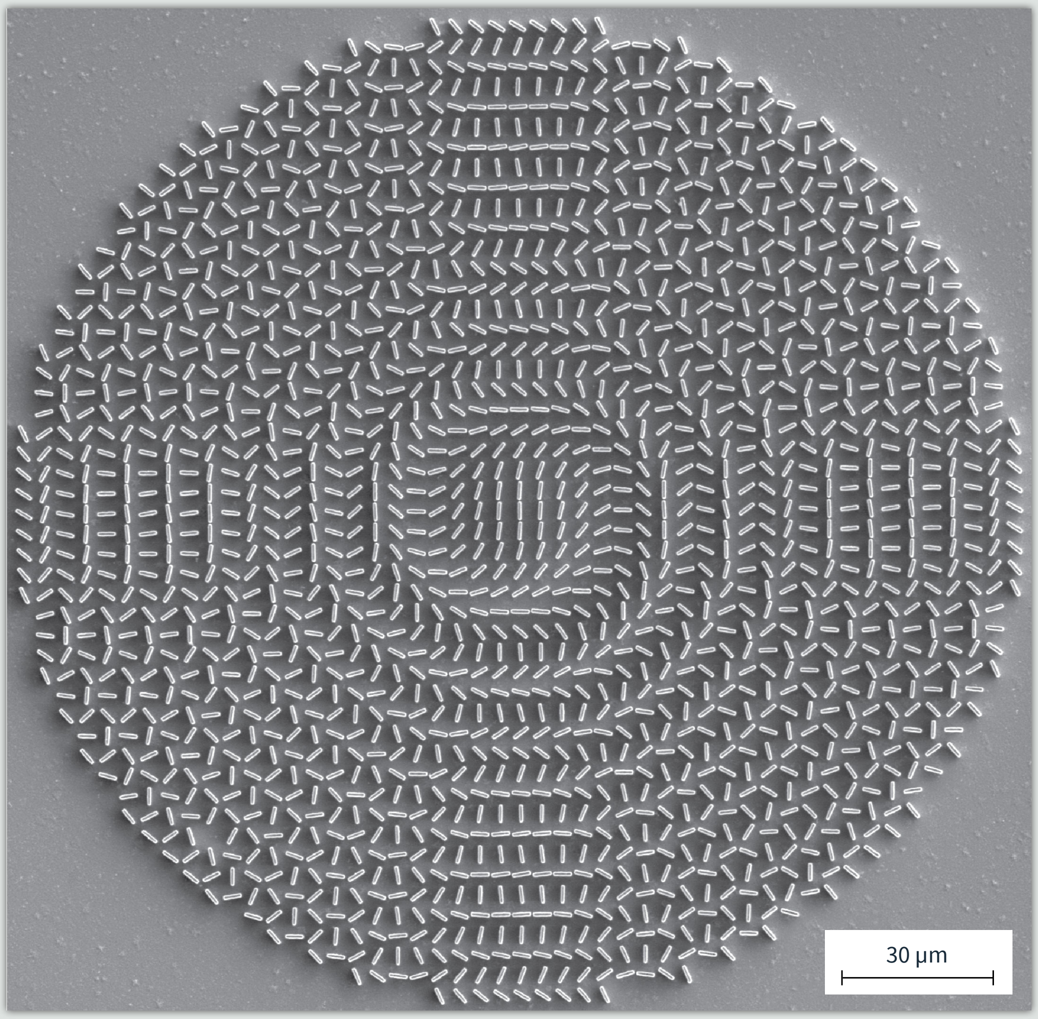

ABSTRACT

Fabricating mid-infrared metalenses using amorphous silicon (a-Si) on calcium fluoride (CaF_2) substrates is challenged by thermal stress during conventional electron beam lithography (EBL), leading to film damage. To address this, a low-temperature lithographic process using the Heidelberg Instruments DWL 66+ direct-write laser system was developed, enabling high-resolution patterning at reduced bake temperatures (95 °C). This approach effectively mitigates thermal mismatch-induced stress, preserving film integrity and enabling the fabrication of high-fidelity metalens structures with gap sizes of 250 nm and aspect ratios of 1:5. The results demonstrate a scalable and robust alternative to EBL for sensitive material systems in mid-IR photonics.

Mid-infrared (mid-IR) flat optics, particularly metalenses, are quickly gaining attention as enabling technology for compact, high-performance optical systems. These planar devices are crucial for advancing applications ranging from chemical sensing and thermal imaging to free-space communication. The core mechanism behind this capability lies in leveraging precisely engineered subwavelength nanostructures to manipulate light.

Metalenses are constructed from arrays of these structures, known as meta-atoms, which serve as the fundamental building blocks of metaoptics. To ensure effective light manipulation in the target mid-IR spectrum (2.5–25 µm), the dimensions of these features must be much smaller than the operating wavelength. The specific metalens structure discussed in this note is based on the theoretical study "Tackling the focal shift effect for metalenses" (Farhan Ali et al., 2024, J. Opt. 26 075103) and employs an amorphous silicon (a-Si) film deposited on a calcium fluoride (CaF_2) substrate. By applying the presented process, it was possible to precisely pattern arbitrarily oriented nanoblocks with an aspect ratio greater than 5, achieving a minimum resolution of 250 nm between the blocks using the DWL 66+ system.

Initial attempts using standard electron beam processing failed due to thermal expansion mismatch between the a-Si film and the CaF_2 substrate. This issue could be resolved by transitioning to Heidelberg Instruments DWL 66+ direct-write laser system. This switch allowed to reduce the photoresist baking temperature, successfully mitigating the thermal stress and at the same time still achieving the required high resolution. In addition, direct laser writing is capable of achieving high throughput which is required for large area patterning while maintaining high uniformity.

This application note details the lithographic steps using the DWL 66+ and the subsequent etching process, demonstrating a high-precision, scalable fabrication method. The full process is illustrated in Figure 2.

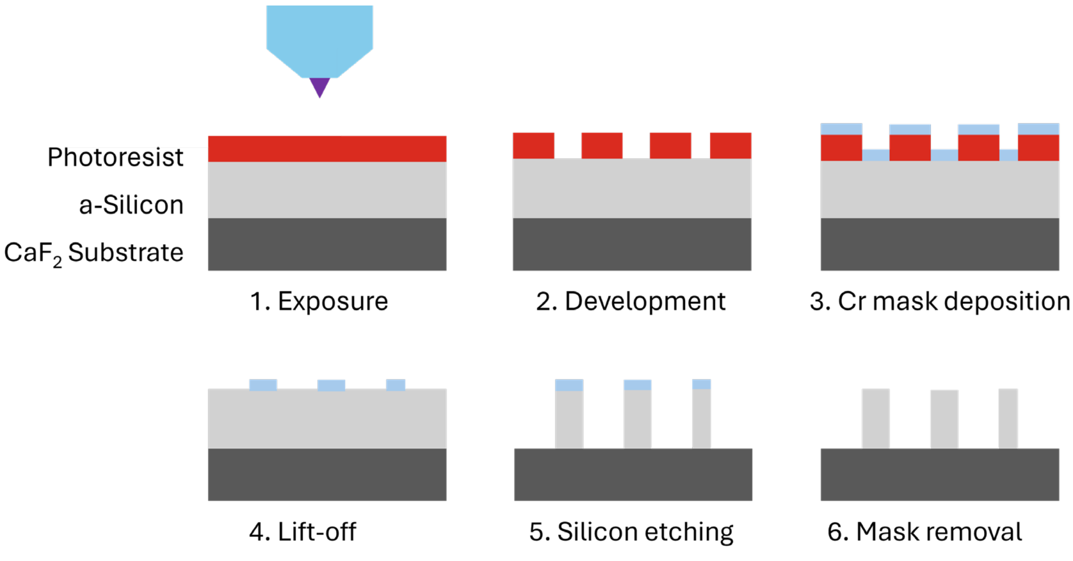

Figure 2: Illustration of the lithographic process for the realization of a metalens

Front page | Figure 1: Top-view SEM image of the entire metalens with a diameter of 200 µm

1. SUBSTRATE PREPARATION AND PHOTORESIST COATING

The process begins with the deposition of an amorphous silicon (a-Si) film of 3.5 micron onto the CaF_2 substrate using magnetron sputtering (KJL PVD 75, Kurt J. Lesker). Next, a positive photoresist layer is prepared. The photoresist is a mixture of AZ5214-E (Merck Performance Materials GmbH) and AZ-EBR solvent (in a 3:4 volume ratio). This mixture is spin-coated onto the a-Si film at 4500 rpm for 45 seconds to achieve a final PR thickness of approximately 300 nm. Critical to minimizing thermal stress is the soft-bake step, which is performed at a low temperature of 95 °C for 25 seconds on a hot plate.

2. PATTERNING AND DEVELOPMENT

The metalens design is transferred into the photoresist using the DWL 66^{+} direct-write laser lithography system using the HiRes Write Mode with a Laser Power of 19 mW (Intensity (%): 50, Filter (%):12.5). Following exposure, the pattern is developed using AZ 726 MIF (MicroChemicals GmbH) for 20 seconds. Using this process, it was possible to achieve features in the resist with minimum gap sizes between the structures of 250 nm as shown in Figure 3.

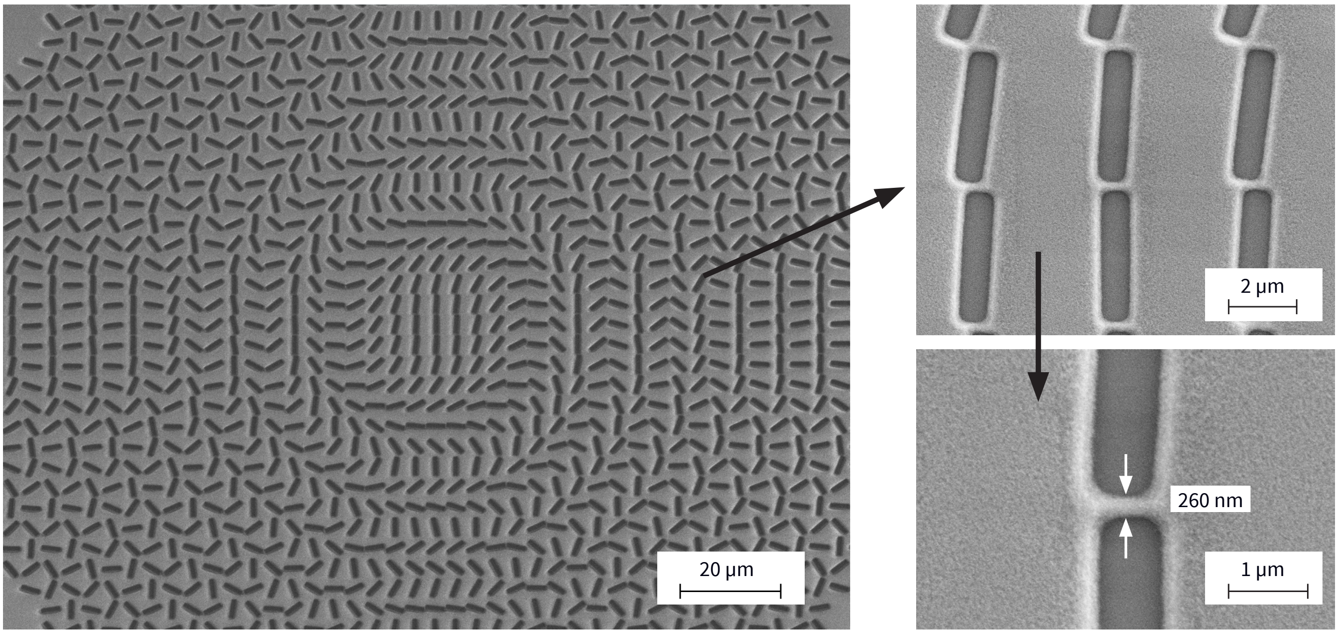

Figure 3: SEM images of the photoresist after the development step

3. HARD MASK DEPOSITION AND LIFT-OFF

A 40 nm thick chromium (Cr) hard mask is deposited onto the photoresist using e-beam evaporation (Pro Line PVD 200 Evaporator, Kurt J. Lesker). A lift-off process is then performed to remove the remaining photoresist and the Cr deposited on top of it, leaving only the Cr mask on the areas intended to be the silicon nanoblocks.

4. SILICON ETCHING (BOSCH PROCESS) AND MASK REMOVAL

The high-aspect-ratio etching of the underlying silicon layer is enabled by applying a Bosch etching process (Sentech SI 500 C). This deep reactive ion etching technique utilizes alternating cycles of SF_6 gas for rapid silicon etching, followed by C_4F_8 gas to passivate the sidewalls, enabling vertical and high-aspect-ratio structures.

Once the desired etch depth is achieved to form the silicon nanoblocks, the Cr hard mask is removed using a commercial Cr etchant. The final metastructures are depicted in Figure 4.

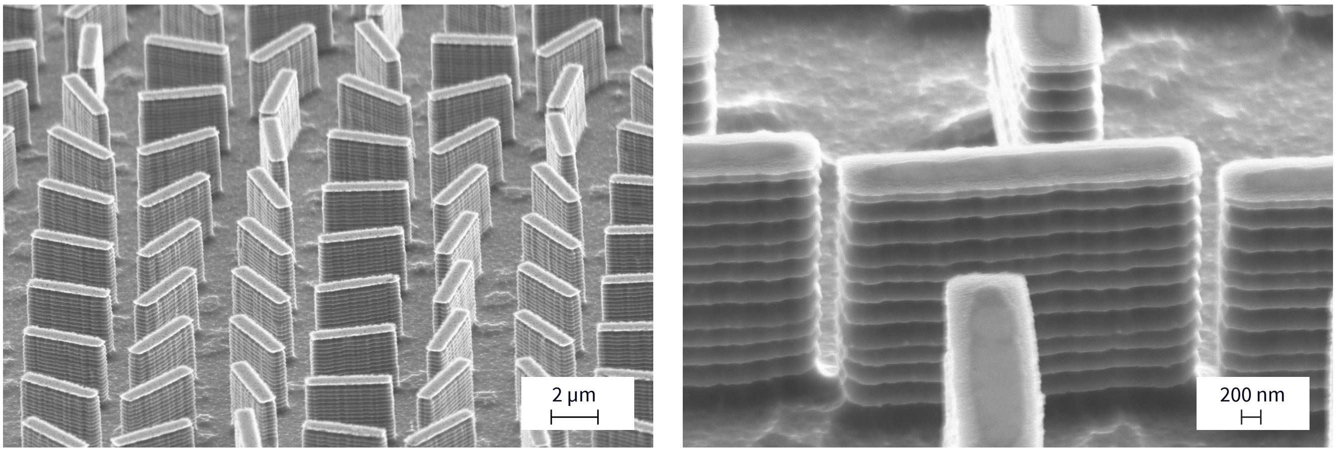

Figure 4: SEM images of the final metalens

OUTLOOK AND FUTURE WORK

A primary limitation of the traditional Bosch process for high-performance metaoptics is the resulting scalloping (a rippling of the sidewalls) on the etched silicon nanostructures. While the Bosch process provides the high anisotropy necessary for achieving the required aspect ratio, the inherent cycling between etching and passivation stages introduces non-idealities that could degrade the optical efficiency of the final metalens.

To address this, future fabrication efforts will incorporate an inductively coupled plasma reactive ion etching (ICP-RIE) step to reduce the scalloping effect. Achieving a high level of surface quality is crucial for minimizing light scattering losses in the mid-IR range.

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