

Fabrication of NiAl and Si Metasurfaces for Wavelength-Selective Thermal Absorption/Emission

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Abstract:

Photonic metasurfaces enable precise control of optical properties at the nanoscale, supporting applications ranging from sensing to thermophotovoltaics. Given that thermal emission and absorption are fundamental material properties, precise spectral tailoring is required to optimize radiative processes used within optoelectronics. Metasurface structures in wavelength-selective thermal emitters shape emission profiles, which by Kirchhoff's law determine absorption under thermal equilibrium. Their functionality can be engineered by tuning parameters such as lattice periodicity, feature geometry, and material composition. These parameters directly influence resonant modes, coupling efficiency, and operating temperature. The periodicity of metasurface structures also facilitates scalability, enabling seamless integration within on-chip devices. By manipulating the amplitude, phase, and polarization of light, metasurfaces provide a versatile platform for compact, multifunctional, next-generation optical devices.

The choice of metasurface material is critical, as it directly impacts its thermal and plasmonic performance. NiAl is a particularly attractive material for high temperature plasmonic applications. It exhibits comparable performance to Mo and W up to 2 μm and to TiN and LaB₆ in the mid-infrared (IR) [1]. It also operates stably in air up to 1000 $^{\circ}\text{C}$. Si provides a robust dielectric medium for metasurfaces supporting quasi-bound states in the continuum (qBIC) modes due to its high refractive index and low optical loss in the near-to mid-IR [2]. This work explores the fabrication of two distinct types of thermal emitters: NiAl microdisk arrays optimized for high-temperature operation, and polycrystalline Si (poly-Si) metasurfaces engineered to support qBIC modes for ultra-narrowband emission.

Summary of Research:

A: NiAl Microdisk Array Fabrication

The fabrication process began by depositing 330 nm

of SiN onto a Si substrate using plasma-enhanced chemical vapor deposition (CVD). A 300 nm NiAl layer was then deposited by direct current (DC) sputtering at a temperature of 500 $^{\circ}\text{C}$. High-temperature in-situ sputtering can induce disorder in a thin film, increasing optical loss. Therefore to achieve a smoother surface film, the initial layer was allowed to cool to room temperature before depositing an additional 250 nm of NiAl. Subsequently, LOR5AE photoresist was spin-coated at 5000 rpm for 60s. A 330 nm MgO hardmask was then deposited by electron beam (e-beam) evaporation. The hardmask provides sufficient etch selectivity to protect the underlying NiAl during the reactive ion etching (RIE) process. After etching, the resulting disk structures had a height of 350 nm. The microdisk geometry is shown in Figure 1. Once fabricated, the NiAl thermal emitters were evaluated in a custom thermal emission setup. The emission spectrum of the NiAl thermal emitters at 300 $^{\circ}\text{C}$ is shown in Figure 2. The optical resonances of the NiAl disk array are attributed to Wood's anomaly, with their spectral position governed by the array periodicity. The two separate peaks may originate from the mode splitting associated with slightly angled alignment of the sample during measurement.

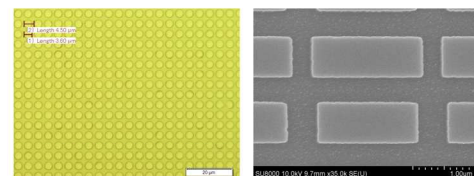


Figure 1: Optical microscope image of the NiAl microdisk array (left) and scanning electron microscope image of the poly-Si qBIC metasurface geometry (right).

B: Poly-Si qBIC Metasurface Fabrication

In preparation for metasurface fabrication, the material properties of the poly-Si were optimized to minimize optical loss. A 200 nm layer of amorphous Si (a-Si) was deposited onto a crystalline Si substrate using radio-frequency (RF) sputtering at room temperature. The samples were then vacuum annealed at varying temperatures (600 $^{\circ}\text{C}$, 650 $^{\circ}\text{C}$, 700 $^{\circ}\text{C}$, and 750 $^{\circ}\text{C}$)

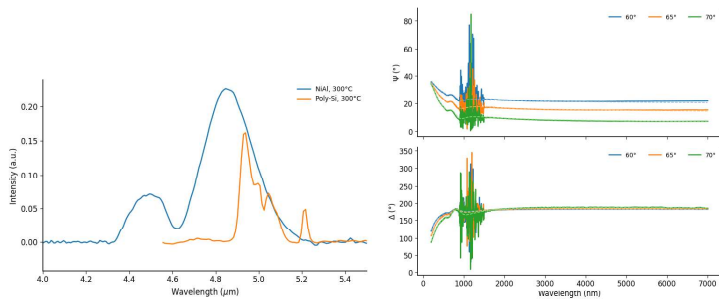


Figure 2 (left): Thermal emission measurements of NiAl microdisk array (blue) and poly-Si qBIC metasurface (orange) thermal emitters at 300 °C. Figure 3 (right): Spectroscopic ellipsometry data (solid lines) and fitting (dashed lines) of a-Si.

to promote crystallization, with the temperature increased at a rate of 10 °C per minute. To characterize the films, the refractive index (n) and extinction coefficient (k) were extracted via spectroscopic ellipsometry to evaluate their optical absorption and dispersion. The optical model used to fit the ellipsometry data for both a-Si and polycrystalline Si incorporated a Bruggeman effective medium approximation (EMA) top layer between air and SiO₂. The a-Si film itself was represented by a spectral combination layer consisting of a Tauc–Lorentz oscillator to describe interband transitions and a Drude–Lorentz term to account for free-carrier absorption. Beneath this, an SiO₂ layer and crystalline Si substrate were included to complete the model. Figure 3 shows the raw spectroscopic ellipsometry data for a-Si (before annealing) for three incident angles (60°, 65°, and 70°), as well as the fitting using the theoretical model.

Anti-Stokes Raman spectroscopy was also employed to examine the vibrational properties of each sample. The full width at half maximum (FWHM) of the Raman spectra was used as a figure of merit for spectral broadening, with narrower peaks indicating reduced disorder and therefore improved crystallinity. The sample annealed at 650 °C exhibited the lowest refractive index, extinction coefficient, and FWHM (Figure 4). Therefore a temperature of 650 °C was used for any subsequent annealing of a-Si.

After establishing the optimal annealing temperature of the a-Si, the dry etching Bosch process was optimized by varying the bias (20 W, 40 W) and inductively coupled plasma (ICP) power (60 W, 80 W, 100 W), with the goal of reducing micrograss formation [3] and surface roughness. This was performed by depositing 1100 nm of poly-Si onto a CaF₂ substrate, following by Bosch etching, and characterization via scanning electron microscope (SEM). Ultimately, a bias of 20 W and ICP power of 100 W was chosen as the optimal dry etching condition (Figure 1). Varying the cycle count enabled extraction of the etch rate from thickness data obtained via spectroscopic ellipsometry.

The fabrication of the poly-Si qBIC thermal emitters employed the same initial stack of 330 nm of SiN and 550 nm of NiAl

deposited on a Si substrate. Subsequently, 1200 nm of SiO₂ and 1280 nm of a-Si were deposited by RF sputtering. The a-Si layer was then vacuum annealed at 650 °C. A positive tone resist of ARP-6200 was then spin-coated at 6000 RPM for 60s. Next, e-beam lithography was performed, followed by Bosch etching of 250 nm to shallow etch the poly-Si layer. After a final water plasma clean, the poly-Si qBIC thermal emitters were evaluated in the same custom thermal emission setup. At 300 °C, the emitters demonstrated a sharp qBIC resonance with a linewidth of 20 nm and an intensity comparable to the NiAl thermal emitter (Figure 2).

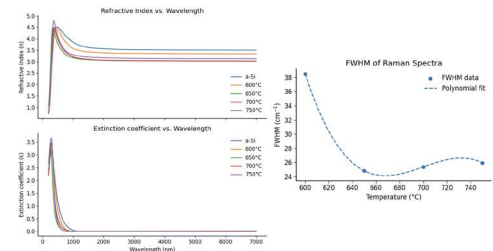


Figure 4: Extraced refractive index, material absorption, and FWHM of vacuum annealed a-Si samples of varying temperatures.

Conclusion and Future Steps:

In this work, we established a complete fabrication process flow for high-temperature NiAl and narrowband poly-Si thermal emitters. The optimized material properties of the poly-Si emitters enabled them to achieve a spectral linewidth of approximately 20 nm. Future efforts will focus on evaluating the performance of NiAl thermal emitters at elevated temperatures (up to 1000 °C), as well as investigating the spectral shifts observed in Si qBIC thermal emission. In particular, potential variations in the a-Si thickness and etch depth will be studied to better understand their influence on device performance.

References:

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