Si-SiO_2 Metamaterial Ultrasonic Lens for Fourier Ultrasonics

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Primary CNF Tools Used: ASML DUV Wafer Stepper, Oxford 81 Etcher, Unaxis 770 Deep Silicon Etcher, Plasma-Therm Deep Silicon Etcher, Thermal Oxidation Furnace

Abstract:

Modern signal processing and machine learning greatly depend on high-performance and power-efficient computation. Fourier transform is one of the most widely used mathematical algorithms in signal processing, speech recognition, and image processing. The complexity of the digital fast Fourier transforms scale in the order of $O(N^2 \log N)$, requiring significant computational resources for large data sets. It has been shown that ultrasonic waves can compute the Fourier transform with a planar lens at the focal length of the input. In this research, we fabricated a planar metamaterial lens that can bend the ultrasonic waves to form the Fourier transform at the lens's focal length.

Summary of Research:

The Fourier transform is a mathematical formula that transforms its time component into the frequency domain. Fourier transform is one of the most widely used algorithms with applications in signal processing, machine learning, and finance. Additionally, the computation power and efficiency of Fourier transform are needed to meet the exponential growth of data in both industries and science. Modern computation frameworks rely on transistor-based processing units. However, it became challenging to continue Moore's law and meet the need for power-efficient computation as the size of the transistor reduced. The Fourier transform using the ultrasonic wave is an alternative solution that can drastically reduce the computation time and power consumption [1-5].

The propagation of waves can be calculated by the Huygens-Fresnel principle. The Huygens-Fresnel principle could be computed from the Rayleigh-Sommerfeld diffraction formula and further simplified for the far-field as the Fraunhofer approximation. However, the Fraunhofer approximation contains an additional quadratic compared to the exact 2D Fourier transform.

In this work, we present a Fourier transform accelerator using the properties of waves. In order to obtain the exact Fourier transform at the receiver side, the accelerator requires a planar lens in front of the transmitter.

Numerous planar binary Fresnel lenses were presented in the past. They consist of binary phase shifts represented by the 2-step size of the lens. In this work, we present a metamaterial lens by fabricating a 4-step size lens and changing the fraction between silicon and SiO_2. This fabrication process only requires a single mask and yields a higher diffraction efficiency which is the ratio between the energy at the focal point and the incoming wave [1-3].

The lens is fabricated by establishing spatially varying SiO_2 pillars inside the silicon wafers that correspond to the different indices of refraction to the passing waves, as shown in Figure 1. The mask is analytically calculated and designed with python to generate the final GDS file. ASML DUV stepper is used for photolithography with pillar diameter of 500 nm - 1 µm. The silicon wafer is etched 16 µm with deep reactive ion etching (DRIE), as shown in Figure 1. SEM pictures are taken after the DRIE

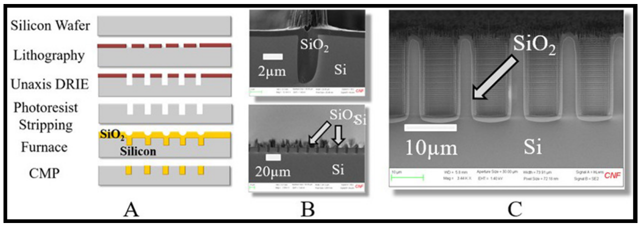

Figure 1: The process flow and SEM pictures after oxidation. A. is the process flow of the ultrasonic lens. B. and C. are the SEM picture after the wet furnace oxidation. The device SEM pictures show the filled trenches of SiO_2 on the silicon wafer [3].

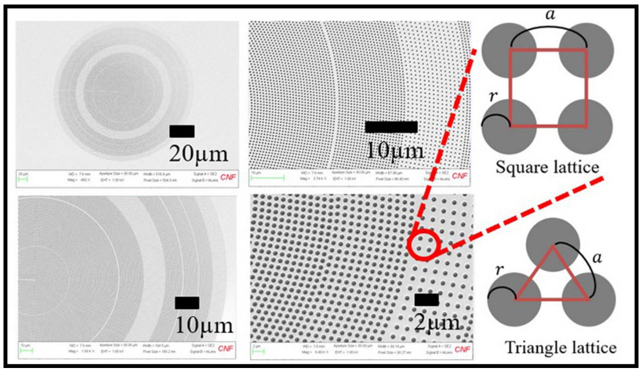

Figure 2: The top-side SEM images of the final device. The varying spatial distribution of the pillar corresponds to a different index of refraction for the acoustic waves. The size of the lens varies from 100 µm to 200 µm in diameter [3].

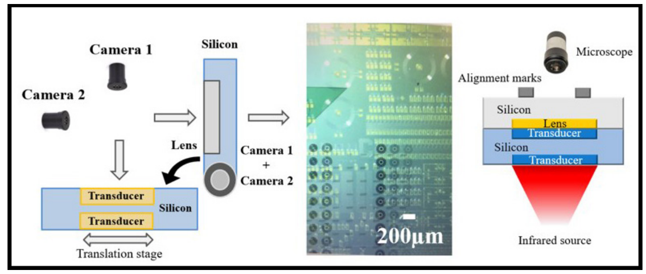

Figure 3: The final lens is bonded to the AlN transmitter using the Pico MA fine-placer. The flip-chip bonder shows the two devices on the same screen overlapping each other [3].

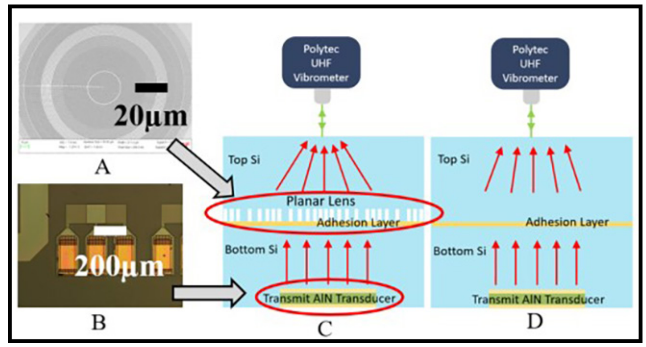

Figure 4: After bonding the lens with the AlN transmitter, the focusing effect is tested with the Polytec UHF [3].

to verify the exact etching rate of the DRIE. Then the trenches are filled with oxide by wet thermal oxidation at 1100°C for 100 minutes. Finally, the device is flattened by chemical mechanical polishing (CMP) and diced using the DISCO.

The final planar metamaterial lens is shown in Figure 2, where the different radii of the pillar spacing represent the different indices of refraction [2].

The final device consists of lenses with a focal length of 500 µm and 1 mm at 1.2 GHz, as shown in Figure 2. After the final fabrication, the device is bonded to the double-sided square transducer actuators fabricated from IME-ASTAR Foundry as shown in Figure 3. The flip chip bonder is used to align the lens and the AlN transmitter for the bonding. Additionally, the infrared microscope was used to verify the alignment after bonding. Finally, the bonded device was tested under Laser Doppler Vibrometry (LDV) to measure the lens's focusing power, as shown in Figure 4 [3].

Conclusions and Future Steps:

In this work, we presented a planar GHz lens that can focus the ultrasonic waves generated from a 100 µm × 100 µm AlN transducer. The lens consists of spatially varying SiO_2 pillars embedded in the silicon wafer to induce different indices of refraction for the incoming waves. The final device was tested using the Polytec UHF to show the focusing effect of the lens at 676 MHz and 1.016 GHz. The demonstrated lens is a preliminary result of the metamaterial lens necessary to make the Fourier transform accelerator.

References:

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