Smart-Cut Processing for Transfer of High-Temperature Ceramic Materials to Silicon

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Abstract:

Micromechanical resonator devices that naturally oscillate at certain frequencies are currently used in communication, signal processing, and sensor applications. Piezoelectric-based resonators, which utilize nonconductive ceramic materials such as quartz, are commonly used for such applications and are historically constructed with a quartz material platform. However, applications with harsh surroundings, such as space environments, combustion engines, and down-hole drilling, can cause failure of quartz resonators at temperatures above 573°C due to phase change of the material and upon radiation exposure. Langatate, a high-temperature crystalline piezoelectric material, is well suited for resonator applications in these environments because of its inherent temperature stability and ability to remain piezoelectric at temperatures above 1400°C.

Here, we are developing a microfabrication technique to place thin langatate films (approximately 1 µm) on a silicon substrate using the "Smart-Cut" process, which involves the exfoliation of a large portion of an ion-implanted langatate piece when heated to high temperatures. Results of spin-on glass bonding, measurements of the hydrophilicity of the langatate surface, and the analysis of the exfoliation of ion-implanted langatate will be presented. Thin-film single-crystal langatate on a silicon substrate can ultimately serve as a platform for the realization of micromechanical resonators for harsh environment applications.

Introduction:

"Smart-Cut" processing has been a major development in the fabrication of silicon-on-insulator (SOI) technologies [1]. This process can also be used to transfer thin-films of other monocrystalline materials, such as langatate, allowing for a uniform high quality crystalline thin-film and has been shown to be successful with silicon carbide, a similar high-temperature material [2]. The langatate thin-film structure will be composed of a silicon wafer, a layer of SiO_2 that improves temperature stability and bonding strength, a coating of spin-on glass acting as an adhesive bond able to withstand high temperatures and forgiving to rough surfaces, and a thin-film of previously hydrogen ion-implanted langatate. The thin-film structure can be suspended by isotropically etching the underlying silicon with XeF_2 gas to obtain a suspended resonator, shown in Figure 1, which has a good quality factor to help keep stable timing [3].

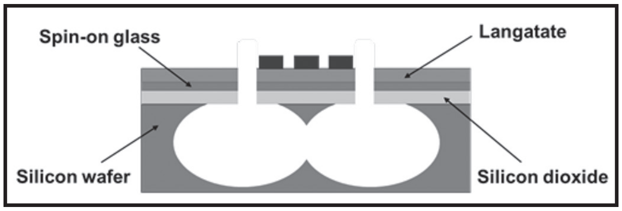

Figure 1: Suspended resonator structure.

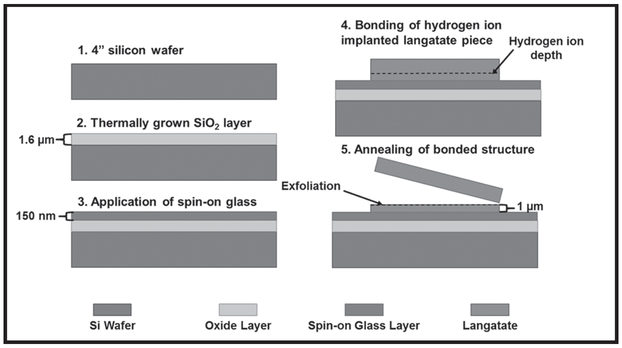

Figure 2: "Smart-Cut" process.

Procedure:

The "Smart-Cut" process is shown in Figure 2. First, a 4-inch silicon wafer topped with a 1.6 µm layer of thermally grown SiO_2 was coated with a 150 nm layer of spin-on glass (hydrogen silsesquioxane). Hydrogen ion-implanted and diced langatate pieces were cleaned with a chemical solution to create a hydrophilic surface. Three pieces were placed on the spin-on glass coated silicon substrate equidistant from one another. A pressure of approximately 1 MPa was applied and the structure was heated to 25°C, 80°C, and 150°C each for one minute and 250°C for four hours. The bonded structure was annealed at temperatures above 600°C to form blisters. These blisters cause the slicing of a large portion of the langatate and leave behind a 1 µm thin-film.

Results and Conclusions:

To ensure that the hydrogen atoms were at a depth of 1 µm, Stopping and Range of Ions in Matter (SRIM) software was employed to find the energy level of the ion beam needed to achieve a large distribution of hydrogen ions at that depth below the surface directly bonded to the substrate. Energies of 170 and 190 keV and a constant fluence of $5 \cdot 10^{16}$ cm^{-2} were chosen for this project.

Exfoliation blisters, which are the precursors to the large portion of material slicing off, appeared when implanted hydrogen atoms were heated and hydrogen gas formed. Atomic force microscopy (AFM) was used to measure the surface roughness of exfoliation blisters, shown in Figure 3, formed after an ion-implanted (170 keV) langatate piece was heated to 950°C for three hours. The depth of the blisters analyzed was approximately 0.6 µm, which was close to our target depth.

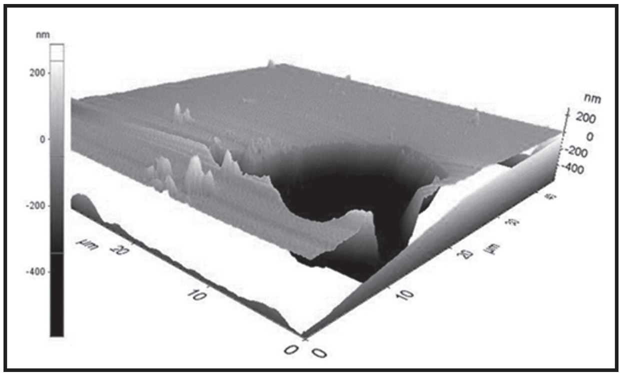

Figure 3: AFM of an exfoliation blister.

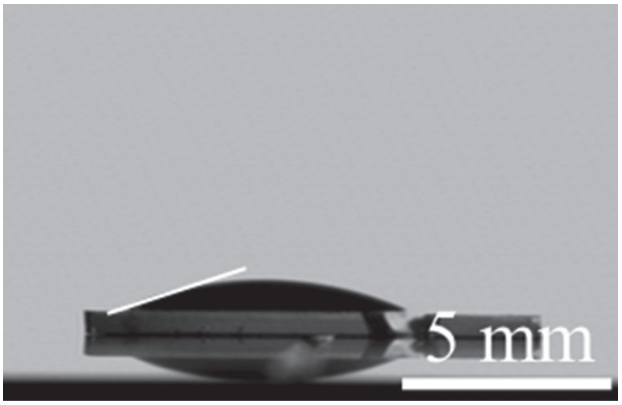

Figure 4: Contact angle of a water droplet on the langatate surface.

Different cleaning methods were implemented on langatate and the hydrophilicity of the surface was examined. After cleaning, the contact angle of a water droplet placed on the surface was measured using a goniometer, shown in Figure 4. A cleaning procedure using HF created a hydrophobic surface. However, changing the chemical clean to a solution of H_2SO_4 and higher percentages of H_2O_2, or piranha clean, led to a hydrophilic surface. Yet, as the time the langatate was left outside of deionized water increased the hydrophilicity of the surface decreased. Therefore, a piranha clean with higher concentrations of H_2O_2 and minimized time outside of deionized water gave optimal results for a hydrophilic surface.

The final step of the "Smart-Cut" process was the annealing of the bonded structure to temperatures over 600°C. However, the spin-on glass bond did not survive when heated up to 950°C. This de-bonding may have been due to a mismatch in the coefficients of thermal expansion (CTEs). Stress calculations were performed and found that langatate and silicon place 48.45 MPa and 55.29 MPa of stress on the spin-on glass bond respectively at temperatures of 950°C. This significant amount of stress being placed on the bond may be the cause of failure.

Future Work:

Future work for this research includes finding new methods of bonding langatate to a silicon substrate, attempting a "Smart-Cut" of langatate on a different substrate with a similar CTE, and ultimately fabricating a suspended resonator from the thin-film structure.

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