LOCALIZED, DEGENERATELY DOPED EPITAXIAL SILICON FOR TEMPERATURE COMPENSATION OF RESONANT MEMS SYSTEMS

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ABSTRACT

A new fabrication method for locally doped silicon resonators is demonstrated within an epitaxial polysilicon encapsulation process (consistent with the established low cost, high yield, high volume manufacturing at SiTime Corporation). Using a cavity etch followed by a selective epitaxial silicon refill with *in situ* degenerate doping, distinct locally doped regions on a 40-µm thick silicon device layer were obtained. Resonators from two different families were characterized for a couple of doping levels and show that temperature sensitivity can be suppressed. This capability removes one of the last remaining disadvantages of silicon as a resonator material, relative to quartz, and should directly enable improvements in the performance, power consumption, and cost of MEMS-based timing products.

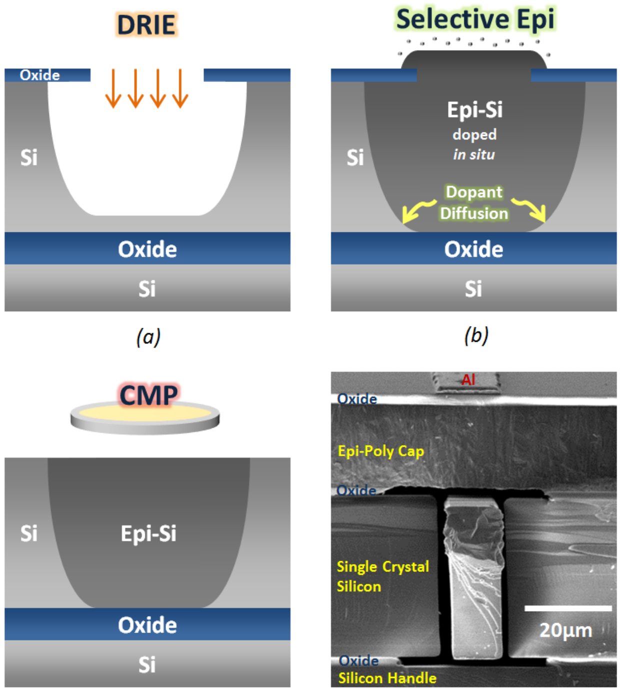
KEYWORDS

Silicon Doping, Resonators, Epitaxial Polysilicon, Temperature Compensation.

INTRODUCTION

Silicon MEMS resonators, with their superior reliability and mechanical resilience [1], are currently replacing quartz resonators in many applications. Yet, one of the disadvantages of silicon resonators is that the resonant frequency varies significantly with temperature (typically about -30 ppm/°C), and is mainly due to the temperature sensitivity of the elastic modulus. While the temperature dependence of quartz resonators can be passively reduced by simply utilizing an appropriately cut crystal (usually the AT cut) [2], silicon resonators conventionally require more complex temperature compensation schemes such as depositing a layer of silicon oxide (which has an opposite elastic modulus dependence on temperature) around the resonator [3], or using a temperature sensor combined with an electronic phase locked loop [4, 5].

Recent work has shown that resonators fabricated in degenerately boron- [6] and phosphorus-doped [7, 8] silicon have a reduced temperature dependence. This passive temperature compensation technique is particularly attractive because of its simplicity in implementation and elimination of possible instabilities due to dielectric charge trapping [9]. Degenerately doped silicon severely strains the crystal lattice, which in turn modifies the electronic band structure [6, 7]. The mechanical properties of a semiconductor are coupled with its electronic band structure through energy conservation, and the modified electronic band structure significantly changes the elastic properties of the silicon crystal [10].



(a) (b) (c) (d)

Figure 1: (a-c) Process flow for thick (~40µm), locally doped single crystal silicon regions on an SOI wafer. (d) Cross-section SEM of a 40µm-thick encapsulated beam resonator in the epi-seal process.

One caveat of temperature compensation by degenerate doping is the requirement for tight control over the doping level. Commercially available Czochralski-grown wafers doped *in situ* during crystal growth have a limited doping range and tolerance levels. The thick functional device layer typically required by MEMS devices (~tens of microns) makes it difficult to dope by conventional diffusion or implantation means [6]. In addition, a thick, degenerately doped silicon layer has a lattice mismatch with lightly doped silicon [11], which manifests itself as strain, resulting in wafer bow issues that impede further wafer processing.

APPROACH

To resolve these issues, a fabrication process has been developed to define a region of single crystal silicon with a different doping level in the device layer (40 µm thick) of a silicon-on-insulator (SOI) wafer (Fig. 1). This involves first hollowing out a cavity in the device layer, and growing silicon back epitaxially in the cavity. Since the doping is done *in situ* during the epitaxial deposition, the doping level can be controlled very precisely with gas flow rates. Choosing only certain regions for degenerate doping (where temperature compensation is required) reduces the overall strain in the wafer and minimizes wafer bow issues. The end result is a wafer with regions that have a substantially different doping level from the field, but is otherwise almost indistinguishable from an unprocessed new wafer. This wafer with localized, degenerately doped regions is compatible with standard fabrication processes and temperature-compensated resonators can thus be defined in these regions without additional process alterations.

In particular, the wafer with localized, degenerately doped regions can be directly used in the *epi-seal* encapsulation process [12, 13] – a proven low cost, high yield, high volume manufacturing process currently in use by SiTime Corporation for silicon MEMS resonators. The *epi-seal* process provides a hermetic, ultra-clean environment that has been demonstrated to be crucial for the stability of silicon MEMS resonators [14].

FABRICATION

The fabrication of locally doped regions (Fig. 1) on a 4" (100mm) SOI wafer begins with growing a 1 µm thermal oxide hard mask on the (100) device layer. A cavity in the 40 µm silicon device layer (~2E19 cm^{-3}, Boron-doped) is then patterned using a deep reactive ion etching (DRIE) tool (Fig. 1a). This cavity defines the region that will be refilled with epitaxial silicon doped *in situ* to the desired level. To prevent keyholes from forming in the epitaxial refilled silicon, the width of the cavity needs to be at least approximately as large as the depth. A more isotropic etch is preferred for ease of refilling; instead of a switched etch-coat DRIE recipe, an SF_6-etch-only recipe was used to define the cavity. Using a timed etch, a thin layer (~1 µm) of single crystal silicon was left at the bottom of the etched cavity to act as a seed for subsequent epitaxial deposition.

Heavily boron-doped epitaxial silicon was then selectively deposited (Fig 1b.) in an Applied Materials Centura Epi tool at 1130°C and 20 Torr with a H_2 carrier gas. Gas flow rates during the deposition were set at: 90 sccm SiH_2Cl_2 (dichlorosilane, DCS); 120 sccm 1% B_2H_6; 490 sccm HCl. As deposition is only desired in the cavity and not on the oxide hard mask, a high HCl to DCS ratio enables a high deposition selectivity between silicon and oxide surfaces – this high selectivity is especially crucial when depositing thick silicon layers. This deposition rate is also highly dependent on the fraction of the wafer available for deposition – for cavities occupying approximately 5% of the wafer, the deposition rate was ~0.75 µm/min. With these gas flow rates, the boron doping level was ~1E20 cm^{-3} (as calculated from the measured resistivity of subsequently fabricated test structures), approximately an order of magnitude higher than the doping level of the original device layer. During the high temperature deposition, it is conceivable that some dopant diffusion occurs at the boundaries, even helping to dope the seed layer of the cavity, but this is unlikely to change the dopant concentration of the epitaxially refilled cavity significantly.

The cavities were refilled until they protruded slightly (~2 µm) from the wafer. Fig. 2 shows a cavity in a bulk test wafer that has been overfilled excessively as the selective deposition rate varies significantly with the area

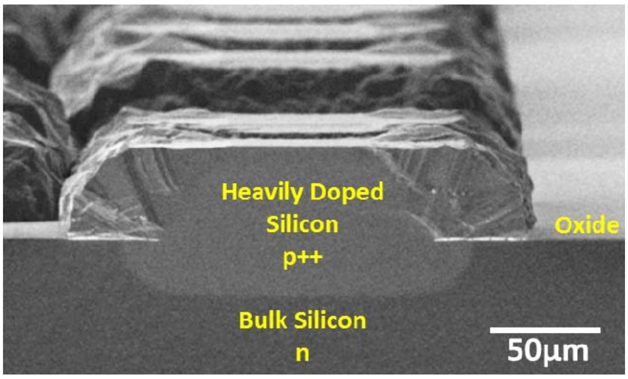


Figure 2: A bulk silicon cavity overfilled with heavily doped silicon (for testing purposes). No silicon grows on the oxide surface with the selective recipe. The boundary between bulk and epitaxially deposited silicon is clearly seen by creating a p-n junction.

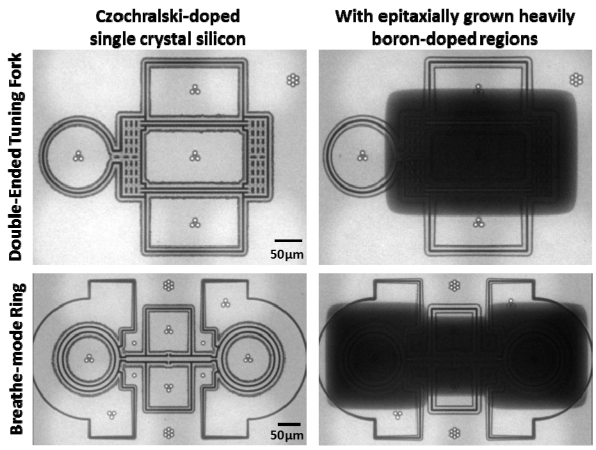


Figure 3: Infrared images of double-ended tuning fork (top row) and breathe-mode ring resonators (bottom row) with (right) and without (left) heavily boron-doped regions. The heavily boron-doped regions absorb more IR radiation and hence appear darker.

available for deposition. A p-n junction was also used for this test to clearly illustrate the boundary between the bulk and epitaxially deposited silicon. For the actual device wafer, the excess protruding silicon (~2 µm) and oxide hard mask were taken off with a chemical-mechanical planarization (CMP) step (Fig. 1c). The resulting wafer is visually indistinguishable from an unprocessed SOI wafer; the fabrication of devices or structures can then proceed on the wafer as with any standard SOI wafer.

This process sequence links seamlessly to an *epi-seal* wafer-level encapsulation fabrication process. Devices were defined in the epitaxially grown regions, and were then encapsulated with an epitaxial polysilicon layer, providing a hermetic, ultra-clean, stable environment for the operation of resonators (Fig 1d). The one observable difference during the fabrication process is that the degenerately boron-doped regions appear much darker under infrared (IR) imaging (Fig. 3) because the high boron doped regions absorb more IR radiation [15]. The difference is apparent when comparing the regions of silicon that were doped during the Czochralski growth process (~2E19 cm^{-3}) to the regions that were doped during the epitaxial refilling (~1E20 cm^{-3}).

EXPERIMENTAL SETUP

The frequency-temperature dependence of two families of resonators was characterized:

1) Double-Ended Tuning Forks (DETF),

2) Breathe-mode Rings,

Resonators with different doping levels (doped either by Czochralski or epitaxial methods) were characterized over a temperature range from -20 to +80°C.

The devices were placed in an environmental chamber and the temperature was allowed to stabilize at each temperature step. Frequency sweeps were performed with an Agilent 4395A Network Analyzer to determine the resonant frequency and quality factor. Trans-impedance amplifiers (TIA) were connected to the DETF output to amplify the signals; a differential drive/sense scheme as presented in [16] was used for the breathe-mode ring resonators.

RESULTS

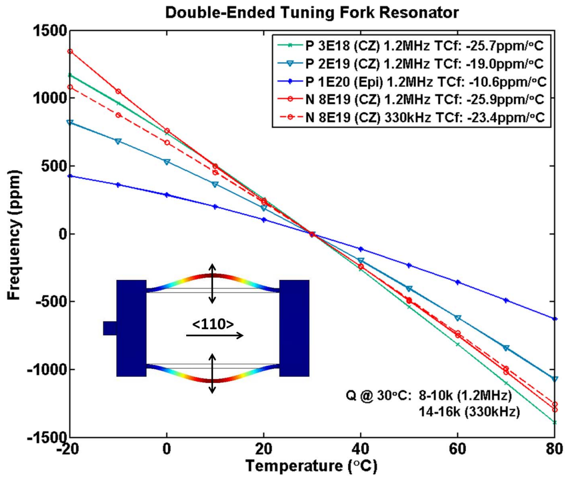
Frequency-temperature curves for the various resonators and doping levels are presented (Fig. 4). First order TCf coefficients are calculated around 30°C. It is seen that the curves vary based on the geometry, vibration mode, and doping level of the resonators.

In agreement with what has been reported in [6], it is noted that boron-doped silicon needs to be doped as heavily as possible (>1E20 cm^{-3}) for significant temperature insensitivity. For heavily phosphorus-doped silicon (~8E19 cm^{-3}), DETFs oriented in the <110> direction show minimal reduction in temperature sensitivity, while breathe-mode rings resonators are temperature compensated well with a turnover point at around 0°C. This is likely to be due to a difference in the TCf between the <100> and the <110> directions, as reported in [7].

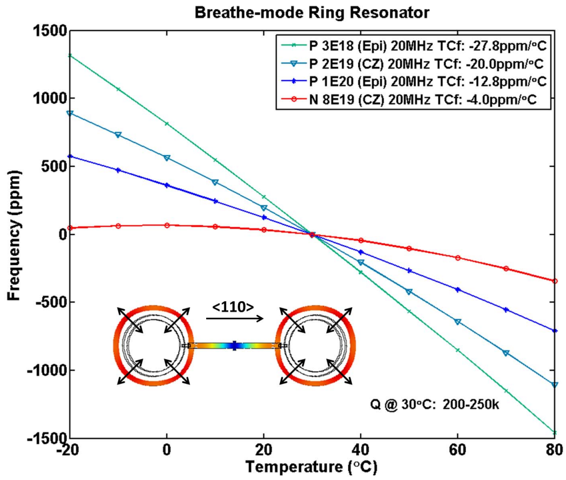
DISCUSSION

This fabrication approach demonstrates the possibility of obtaining distinct regions with different doping levels on a thick device layer of an SOI wafer and directly enables several applications for high performance MEMS resonators:

1) With the correct choice of doping and resonator geometry, the first-order TCf of Silicon MEMS resonators can be eliminated.
2) The compatibility of this result with an existing low cost, high yield, and high volume process at SiTime Corporation enables immediate use of this capability.
3) Lightly doped resonators with a large TCf can be used as high resolution temperature sensors for the temperature compensation of adjacent heavily doped, low-TCf resonators in the same chip for high-precision timing applications.
4) Doping for TCf suppression can also be used for precision resonant gyroscopes, accelerometers, or other resonant MEMS devices intended for operation over wide temperature ranges.



(a)



(b)

Figure 4: Frequency-temperature dependence on doping type and concentration for p-type (boron) and n-type (phosphorus) for (a) Double-ended tuning fork resonators in the <110> direction, (b) Breathe-mode ring resonators. Localized epitaxially doped resonators (Epi) and Czochralski-doped resonators (CZ) were tested. TCfs were calculated at 30°C.

CONCLUSION

A fabrication method for obtaining distinct, locally doped regions on a thick silicon layer is presented. By etching a cavity and refilling using local, selective epitaxial silicon deposition, the doping level can be well controlled. This technique with the hermetic, ultra-clean *epi-seal* encapsulation process, which has been demonstrated to be crucial for resonator stability. The frequency-temperature sensitivity of resonators from two distinct families with different doping types/levels was characterized, and it is seen that the temperature sensitivity varies based on the geometry, vibration mode, and doping level of the resonators. With the right choice of parameters, temperature sensitivity can be reduced significantly.

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