EFFECTS OF BORON CONCENTRATION ON Si$_{1-x}$Ge$_x$ PROPERTIES FOR INTEGRATED MEMS TECHNOLOGY

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ABSTRACT

The effects of boron (B) concentration on the chemical, electrical, and mechanical properties of p+ polycrystalline germanium (poly-Ge) and p+ polycrystalline silicon-germanium (poly-Si$_{1-x}$Ge$_x$) films are reported. Experimental results show that heavy B doping is beneficial for increasing the deposition and etch rates, as well as for reducing the surface roughness of p+ poly-Ge sacrificial films. However, structural poly-Si$_{1-x}$Ge$_x$ films become more compressive, and show a slight increase in strain gradient, with increasing B content. Analytical models fit to the experimental data for conductivity, residual stress, and strain gradient have been generated as a guide for co-optimization of B and Ge content.

INTRODUCTION

Polycrystalline silicon-germanium (poly-Si$_{1-x}$Ge$_x$) is an attractive material for post-CMOS integration of MEMS with electronics because it can be used to form high-quality structural films with a thermal process budget that is compatible with standard electronics [1-2]. Germanium (Ge) is an attractive sacrificial material because it can be deposited rapidly at low temperatures (< 350°C) and readily etched selectively to metals, Si, SiO$_2$, Si$_3$N$_4$, and Si$_{1-x}$Ge$_x$ (x < 0.7) in a heated peroxide (H$_2$O$_2$) solution [3]. In situ p-type doping is preferred because it provides enhanced deposition rate and lower resistivity [1]. Previous studies of structural poly-Si$_{1-x}$Ge$_x$ layers focused on very heavily boron doped films (B concentration exceeding 10$^{20}$ cm$^{-3}$) for minimum electrical resistivity (<1 m$\Omega$-cm) and maximum deposition rate. Recently, however, heavy boron doping was reported to enhance the etch rate of p+ Si$_{1-x}$Ge$_x$ (x > 0.7) in H$_2$O$_2$, which compromises the etch selectivity between the p+ Ge sacrificial material and the Si$_{1-x}$Ge$_x$ structural layer(s) during the long etch needed to release the MEMS structures [4].

The effects of boron concentration on the properties of poly-Ge films and poly-Si$_{1-x}$Ge$_x$ films are presented in this paper, which aims to highlight the tradeoffs for process optimization. The B-doping dependence of Ge deposition rate, etch rate, and surface roughness is first discussed. Experimental data are then reported for p+ Si$_{1-x}$Ge$_x$ (x < 0.7) films, to show the effects of boron content on residual stress and strain gradient. It should be noted that all of the films studied in this work are suited for post-CMOS processing, since they are deposited at a temperature less than or equal to 425°C with no post-deposition annealing treatment.

EXPERIMENTAL DETAILS

P-type Ge films were deposited at 350°C and 300mT onto oxidized Si wafers, with a very thin (<10nm thick) amorphous-Si seed layer, in a conventional low-pressure chemical-vapor deposition (LPCVD) system using GeH$_4$ (170 sccm) as the Ge precursor gas, and B$_2$H$_6$ as the dopant gas. The B$_2$H$_6$ is diluted to (10%) in H$_2$ and is introduced from the back of the furnace through an injector in order to minimize gas depletion effects, while the GeH$_4$ is simply introduced through a ring at the front of the tube. Because of this arrangement, the B concentration and Ge content are dependent on wafer position inside the tube (Fig. 1). The B concentration in each of the deposited films was determined by Secondary Ion Mass Spectrometer (SIMS) analysis. The sheet resistance of the films was measured at several points on each wafer using a four-point probe instrument; average values are reported herein. The Ge films were patterned into test structures using conventional optical lithography and reactive ion etching (RIE) using Cl$_2$/HBr chemistries. The film thickness was then determined from step-height measurements using a Dektak surface profilometer. The Ge etch rate in a 90°C H$_2$O$_2$ solution was then characterized by monitoring the thickness in-between etch treatments, for films of various Ge contents.

P-type poly-Si$_{1-x}$Ge$_x$ films were deposited at 425°C and 400mT in the same LPCVD system, onto oxidized Si wafers (p-type, 1 ohm/square) coated with ~2.2µm of undoped low temperature oxide (LTO). SiH$_4$ was used as the precursor Si gas (Fig. 1). The B concentration and Ge content in the deposited films were determined by SIMS analysis (2.5% accuracy), and varied from 1×10¹⁵ cm$^{-3}$ to 5×10¹⁷ cm$^{-3}$ and 61% to 67%, respectively. In order to determine thin film stress, wafer curvature measurements were made using a Tencor FLX-2320 instrument before and after Si$_{1-x}$Ge$_x$ deposition (with the backside Si$_{1-x}$Ge$_x$ film removed). The films were patterned into cantilever-beam test structures (Fig. 2) and then released using a timed etch in 49% concentrated HF. Then, a Vecco Instruments WYKO interferometer was used to measure the tip deflection of 100µm- and 50µm-long beams to determine the strain gradient.

![Figure 1: Schematic Diagram of LPCVD furnace that was used to deposit p+ sacrificial Ge and p+ structural Si$_{1-x}$Ge$_x$ films.](image-url)
RESULTS AND DISCUSSION

A. Effect of Boron Doping on Sacrificial Ge Properties

Ideally, a sacrificial material is deposited at a high rate with minimal surface roughness, and is rapidly and controllably etched selectively to the structural material. Thus, we investigated the deposition rate, etch rate (in a 30% H₂O₂ solution maintained at 90°C), and surface roughness of p+ Ge films as a function of B concentration ([B]). Fig. 3 shows that the deposition rate increases with [B], and saturates above ~1.8×10²¹ cm⁻³ at a deposition rate of ~160Å/min. The etch rate also increases with [B]. As expected, the resistivity drops with increasing [B] (Fig. 4). However, it shows an abrupt increase at ~2×10²¹ cm⁻³ since that deposition condition leads to an amorphous film. Because of the enhancement in deposition rate that accompanies an increase in [B], the atoms adsorbed on the wafer surface have less time to migrate to the lowest energy crystal sites before the next atoms arrive. Thus, as [B] increases, the degree of disorder in the film increases (average grain size decreases – see Fig. 6), until ultimately the film is deposited in amorphous form at very high levels of [B].

Atomic force microscopy (AFM) measurements indicate that the more heavily boron doped Ge films are smoother (Fig. 5), which is consistent with their higher deposition rate (resulting in smaller average grain size – see Fig. 6). Clearly, high [B] is desirable for increasing process throughput, etch selectivity, and film smoothness for sacrificial Ge films. It is important to note that, although the deposition rate can be substantially increased by increasing the deposition temperature, the film roughness also increases. Thus, it is preferable to keep the p+ Ge deposition temperature below 400°C.

B. Effect of Boron Doping on Structural Si₁₋ₓGex Properties

The etch rate of p+ poly-Si₁₋ₓGex films in a 30% H₂O₂ solution maintained at 90°C was measured and found to be relatively low (25Å/min) and independent of B concentration, for...
films with Ge content below 65%. Thus, good etch selectivity between sacrificial p+ Ge and structural Si$_{1-x}$Ge$_x$ can be achieved so long as $x$ does not exceed 0.65. The conductivity of poly-Si$_{1-x}$Ge$_x$ films as a function of B concentration is plotted in Fig. 7, and is seen to improve with increasing [Ge] as well as increasing [B]. This is likely due to improved dopant activation and hole mobility with increasing Ge content [5], due to increased grain size [6].

Using a regression analysis methodology that accounts for all the measured data, the best-fitting surface plots for conductivity, residual stress, and strain gradient as a function of B concentration and Ge content were generated (Fig. 7 and Fig. 8). The fitting confidence is 99.5% for conductivity, 89% for residual stress, and 81% for strain gradient. Electrical and mechanical properties each improve with increasing Ge content. Thus, the Ge content should be maximized at ~65%, so that good etch selectivity of Ge in heated H$_2$O$_2$ solution is maintained.

For [B]=2.5×10$^{20}$cm$^{-3}$, the strain gradient is 1.3×10$^{-3}$ μm$^{-1}$, which corresponds to a vertical deflection of 1.7 μm at the tip of a 100 μm-long, 0.8 μm-thick cantilever beam. Although this is too high for inertial MEMS device applications (e.g., accelerometers and gyroscopes), it may be acceptable for nanoscale MEMS devices such as RF filters. Approaches to reducing the strain gradient include the use of a bi-layer [7] and the use of pulsed excimer-laser annealing (ELA) [8]. Based on the best-fit analytical models, the optimal B concentration for a low resistivity poly-Si$_{0.42}$Ge$_{0.58}$ film is ~5.1×10$^{20}$cm$^{-3}$ to achieve minimal residual stress (~0.0012 MPa) and strain gradient (~3.75×10$^{-3}$ μm$^{-1}$). However, it is important to note this optimal point is an approximation since the models are based on relatively few data points.

Hall measurements were performed to compare the dopant activation level in two p+ Si$_{0.37}$Ge$_{0.63}$ films: Sample A (with [B] $\approx$ 4.5×10$^{19}$ cm$^{-3}$, $\sigma$ = -22 MPa) and Sample B (with [B] $\approx$ 9.7×10$^{20}$ cm$^{-3}$, $\sigma$ = -79 MPa). The results are summarized in Table I, and they indicate that all of the B is activated in Sample A, whereas this is not the case for Sample B. Therefore, the fact that the p+ Si$_{1-x}$Ge$_x$ structural films become more compressive at very high B concentrations is likely due to segregation/clustering of boron atoms.
Due to the large strain gradient which causes the released structures to bend up (out of plane), it was not possible to operate the fabricated comb-drive test structures in order to obtain measurements of the mechanical quality factor (Q) for this study. Q values of ~20,000 at 19 kHz resonant frequency have previously been reported for very heavily doped (~[B] > 6x10^{19} cm^{-3}) poly-Si_{0.38}Ge_{0.62} films [9]. The Q was found to increase with post-deposition annealing (RTA) temperature. To investigate possible causes for this change, we annealed similarly doped poly-Si_{0.38}Ge_{0.62} films for 1 minute at 600°C in N_2 at various temperatures (450°C to 600°C) and then performed Hall measurements as well as X-ray diffraction (XRD) analyses. The Hall measurement results did not indicate a significant increase in dopant activation with annealing, which would suggest that excess (non-ionized) B atoms remain. The XRD analysis results show that the as-deposited film has weak (111) texture, which changes to a strong (110) texture after a rapid thermal annealing treatment. The diffraction peaks for the annealed films were significantly larger and narrower, indicating a larger average grain size, as well. Thus, it seems that the improvement in Q with annealing is attributable to improved microstructure, rather than a reduction in segregated B atoms.

C. Ge and B Quantification by SIMS

Since SIMS was used in this work to quantify the concentrations of B and Ge atoms in the Si_{1-x}Ge_x films, it is appropriate to highlight here some of the limitations of this characterization technique. SIMS is based on the linear relation between the concentration of the element of interest and its secondary ion yield in a given matrix. It was shown that correctly chosen analytical conditions and quantification techniques allowed SIMS analysis to generate highly accurate and precise data for B implants into Si_{1-x}Ge_x structures for bipolar applications [10]. SiGe bipolar structures are typically characterized by relatively small contents of Ge, up to 10-15 atomic percent. On the other hand, CVD layers for MEMS applications require very high Ge contents, typically 60-70%. The ability to perform highly accurate quantification of doping elements in high Ge content Si_{1-x}Ge_x films is a major challenge for SIMS. In the current study, quantification of Si and Ge was done with a Si_{0.4}Ge_{0.6} epitaxially grown standard and the so-called “missing Si” approach. SIMS measurements were performed on Cameca 4FE7 secondary ion mass-spectrometer, with 4 keV Cs+ primary ion beam and negative detection mode (28Si; 70Ge, 11B28Si; 11B70Ge). The measurement uncertainty achieved in the current study was 2.5% atomic concentration and was assessed by performing SIMS measurements on identical samples.

Table I: Hall Effect Measurement Results for p+ Si_{0.37}Ge_{0.63}.
Sample A (σ = -22 MPa), Sample B (σ = -79 MPa)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sample A</th>
<th>Sample B</th>
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<tbody>
<tr>
<td>Boron</td>
<td>4.5x10^{19} cm^{-3}</td>
<td>9.7x10^{19} cm^{-3}</td>
</tr>
<tr>
<td>Carrier</td>
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CONCLUSION

In-situ B doping is beneficial for improving the deposition and etch rate, as well as the surface smoothness, of LPCVD p+ Ge sacrificial films. Heavy B doping does not increase the etch rate of poly-Si_{1-x}Ge_x structural films in heated H_2O_2 solution, as long as the Ge content is below 65%, so that high etch selectivity can be maintained for a Ge sacrificial material. Increasing the B concentration is beneficial for decreasing electrical resistivity, but results in more compressive stress at very high concentrations, as well as slightly higher strain gradient.

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REFERENCES