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Dopant profile engineering by near-infrared femtosecond laser activation

Yi-Chao Wang and Ci-Ling Pan

Department of Photonics and Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan, Republic of China

Jia-Min Shieh and Bau-Tong Dai

National Nano Device Laboratories, Hsinchu 30078, Taiwan, Republic of China

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Femtosecond laser annealing (FLA) was employed for activation of phosphorus (P) and boron (B)-implanted silicon with negligible dopant diffusion. Preamorphizing implantation is not required. We found that the dopant profiles in FLA-activated samples essentially duplicate those of as-implanted ones even for junctions as deep as 100 nm below the surface. The shallow activated-depth feature associated with FLA reduces the separation between end-of-range defects and high-concentration portion of dopants. This generates a steep interstitial gradient responsible for observed B and P uphill diffusions at a depth of about 60 nm below the surface. © 2006 American Institute of Physics. [DOI: 10.1063/1.2191095]

Much effort has been focused on the formation of thin insulators, short channels, and shallow junctions by dopant profiling for scaling of transistor-based silicon devices to ~100 nm. State-of-the-art dopant profile engineering is achieved by integrating low-energy implantation, defect engineering, fast solid phase epitaxial regrowth or laser annealing. To date, dopant profile engineering still faces challenges such as boron-enhanced diffusion, transient-enhanced diffusion, boron-interstitial clustering, and uphill diffusion. In comparison, activation by nanosecond excimer laser annealing (ELA) can more effectively minimize dopant diffusion than furnace annealing (FA) and spiked rapid thermal processing (RTP). Nevertheless, dopant diffusion during ELA-based activation is not eliminated altogether. This is generally attributed to both vacancy- and interstitial-mediated diffusion mechanisms that are enhanced by a rapid melting and solidification process. Recently, we reported femtosecond laser (λ=800 nm) annealing (FLA) of amorphous silicon (a-Si). In this work, we report FLA-activated n-type (phosphorus or P) and p-type (boron or B) dopants confined in ultrashallow junction regions. Preamorphization by implantation (PAI) is not required.

We employed a 1 kHz Ti:sapphire regenerative amplifier (λ=800 nm), generating 50 fs pulses, and a line-scan FLA (Ref. 11) to activate P- or B-implanted Si substrates. To compare, PAI by Si⁺ as well as the use of BF²⁺ instead of B⁺ for implantation were employed for some of the samples. ELA activation experiments using a KrF laser (λ=238 nm) were also conducted. The samples and processing parameters studied are summarized in Table I. Dopant profiles for activated and as-implanted samples were analyzed by secondary ion mass spectrometry (SIMS) and spreading resistance profiling (SRP) for assessment of the active and retained dose. Sheet resistances of all samples were measured by using a four-point probe.

Figure 1 shows SIMS profiles of borons in B-implanted layers without (sample A) and with PAI (sample B) as well as as-BF²⁺-implanted layers (sample C). Junction depths for the three as-implanted samples were designed to be 270, 200, and 100 nm, respectively. The SIMS and SRP measurements of boron in low-energy B-implanted layers (sample C) and phosphorus in low-energy P-implanted layers with a junction depth of 100 nm (sample D) are shown in Figs. 2 and 3. Laser fluences required for activating all the samples were 27–39 vs 45 mJ/cm² for FLA crystallization of a-Si films. Sheet resistances for all FLA-activated samples were in the range of 100–400 Ω/□.

After FLA activation at room temperature (24 °C), dopant profiles of all activated samples were found to be almost the same as those of as-implanted ones (see Figs. 1 and 2). No flat-top profiles were observed in regions of highly concentrated dopants, as opposed to the cases for activation by ELA. This implies the absence of dopant redistribution by FLA activation. The laser fluence required for FLA activation is 0.5 J/cm², much lower than that for ELA activation (5–10 J/cm²). Either linear or nonlinear absorption of laser photons by implanted samples is not expected to reduce the required activation fluence. The low fluence required for FLA activation thus suggests that ultrafast or nonthermal melting of semiconductors is the dominant mechanism. Irradiated by femtosecond pulses that photoexcited a large enough fractions of the valance electrons in the semiconductor, the lattice is weakened and a structural change can occur while the electronic systems of the lattice are not in thermal equilibrium with each other. Such a nonthermal melting mechanism could minimize dopant diffusion significantly by reducing the thermal budget of activation.

For FLA activation of samples at room temperature, we show in Fig. 1 that dopant diffusion after activation is negligible in samples A and B. The peak position in B dopant profile of sample C after FLA activation, however, shifts by about 10 nm with respect to that of as-implanted sample C.
This is independent of the substrate temperature up to 200 °C. We also observed uphill diffusion towards the surface by ~10 nm for sample C at profile depth beyond ~60 nm. Uphill diffusion is more apparent at elevated substrate temperatures. In samples A and B, on the other hand, no uphill diffusion was observed. We note that uphill diffusion in dopant profiles for silicon activated by other methods often occurs at a depth as shallow as 10 nm.3,6,14 For P dopant profiles in sample D without substrates heating see Fig. 3, uphill diffusion at a depth of 60 nm is barely observable, whereas P atoms diffuse away from the surface by ~10 nm at elevated temperatures.

Electrical profiling (SRP) of active B and P in samples C and D, respectively, were conducted and shown in Figs. 2 and 3. Increasing the substrate temperature from 24 °C to 200 °C, the activation efficiency (dose activated/dose implanted) of sample C (D) increases from 28% (31%) to 33% (36%). At the same time, the sheet resistance of sample C (D) decreases from 450 (325) to 225 (225) Ω/□. These values are similar to reported ELA results.8

### Table I. Implantation parameters and FLA-activation and ELA-activation conditions for three B-doped and P-doped layers. Sheet resistances for doped layers activated by FLA with those activated by ELA methods in this work and reported in Refs. 4 and 5 are listed for comparison. Dopant depth is defined as the distance from the surface at which the dopant concentrations drop to 10^{18} cm⁻³.

<table>
<thead>
<tr>
<th></th>
<th>B-implanted a-Si (without PAI)</th>
<th>B-implanted Si (with PAI)</th>
<th>BF sub-implanted Si</th>
<th>P-implanted Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si PAI parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dopant implantation parameters</td>
<td>20 keV 5 × 10^{15} cm⁻²</td>
<td>20 keV 5 × 10^{15} cm⁻²</td>
<td>25 keV 5 × 10^{15} cm⁻²</td>
<td>15 keV 5 × 10^{15} cm⁻²</td>
</tr>
<tr>
<td>Fluence used for FLA (ELA) (mJ/cm²)</td>
<td>37–39</td>
<td>30–34</td>
<td>27–29 (250)</td>
<td>31–33 (250)</td>
</tr>
<tr>
<td>Number of laser shots for FLA (ELA)</td>
<td>20</td>
<td>20</td>
<td>20 (20)</td>
<td>20 (20)</td>
</tr>
<tr>
<td>Junction depth (as implanted) (nm)</td>
<td>~270</td>
<td>~200</td>
<td>~100</td>
<td>~100</td>
</tr>
<tr>
<td>Sheet resistance of FLA-activated samples (Ω/□)</td>
<td>100–250</td>
<td>200–400</td>
<td>225–450</td>
<td>225–325</td>
</tr>
<tr>
<td>Sheet resistance of RTA-activated samples (Ω/□)</td>
<td>280–300</td>
<td>190–300</td>
<td>180</td>
<td>160</td>
</tr>
</tbody>
</table>

aReference 4.

bReference 5.

This work.
diffusion of boron atoms is also apparent in SRP curves for sample C FLA activated at 24 and 200 °C (see Fig. 2). In the same figure, we show the flat-top profiles of ELA activation for sample C at 24 and 200 °C. Uphill diffusion phenomena in ELA-activated samples C and D are not observed. This is also shown in Figs. 2 and 3. It is obvious that, in the melting regime, ELA obliterates any effect of substrate temperature. One might consider comparing nonmelting ELA performed at 200 °C with FLA at the same temperature. For the former case, it is reported that boron exhibited negligible diffusion during each pulse and the sheet resistance values could not be measured by the four-point probe because the values were too high.\(^1\) That is, activation by nonmelting ELA is ineffective, while we have shown that FLA activation is very successful.

Using femtosecond laser pulses, ultrafast or nonthermal melting of the sample surface rather than heat penetration due to thermal conduction\(^\text{13}\) is expected to lead to a thinner melting depth in FLA-annealed samples. This limits the activation depth and thus prevents thermally assisted diffusion of end-of-range (EOR) defects further away from the surfaces. As a result, trapped interstitials will remain within the EOR regions for FLA, accomplishing the functionality of PAI in ELA.\(^\text{3,6}\) This model is corroborated by the observation of end-of-range (EOR) regions for FLA, accomplishing the functionality of FLA annealed samples. This limits the activation depth feature associated with FLA reduces the separation between end-of-range defects and high-concentration portion of dopants. This generates a steep interstitial gradient responsible for observed P and B uphill diffusions at a depth of about 60 nm below the surface.

Heating of the samples during activation will render the interstitials more mobile.\(^\text{5}\) For BF\(_\text{2}\)-doped layers, elevated substrate temperature likely facilitates the generation of more boron-interstitial pairs, thereby promoting B uphill diffusion.\(^\text{6}\) Uphill diffusion of P atoms in shallow P-implanted layers FLA activated at elevated substrate temperature were not observed (see Figs. 2 and 3). The diffusivity of P atoms doped is much higher than that of B atoms in Si;\(^\text{15}\) underlying the different behavior for B and P and consistent with observation that the dopant profile of the P-implanted layer is broader than that of the BF\(_\text{2}\)-implanted sample for ELA activation.

In summary, femtosecond laser annealing (FLA) was employed for activation of P- and B-implanted silicones with negligible dopant diffusion. Preamorphization by implantation, commonly used in conventional activation schemes for minimizing the diffusion of dopant during annealing, is not required. We find dopant profiles in FLA-activated samples essentially duplicate those of as-implanted ones even for junctions as deep as 100 nm below the surface. The measured sheet resistances and activation efficiencies of P- and B-implanted samples were in the range of 100–400 Ω/□ and 28%–35%, respectively. Moreover, thermal-energy-assisted dopant diffusion by heating was observed for substrate temperature as low as 100 °C. The shallow activated-depth feature associated with FLA reduces the separation between end-of-range defects and high-concentration portion of dopants. This generates a steep interstitial gradient responsible for observed B and P uphill diffusions at a depth of about 60 nm below the surface.

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\(^12\) S. K. Sundaram and E. Mazur, Nat. Mater. 1, 217 (2002).