

Directly Pumped Silicon Lasing

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Abstract: Enhanced photoluminescence and 1.28 μm laser emission from nano-engineered silicon originating respectively from phonon k -selection rule breaking and point defect-mediated phononless recombination in an array of Emissive Structural Deformation zones in a SOI wafer are reported.

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1. Nano-patterning for light emission in crystalline silicon

Despite the indirect band gap, efforts have been devoted to making silicon an efficient light-emitter [1-3], including a most recent observation of low-temperature laser emission at 1.28 μm [4,5]. We present here a study of the relevant physical mechanisms in the nano-engineered crystalline silicon and examine the possibility of lasing at higher temperatures and the results of enhanced photoluminescence at room temperature.

The periodically nanopatterned silicon structure was fabricated in undoped crystalline electronic-grade silicon-on-insulator (SOI) using a highly-uniform self-assembled nanopore array as an etch mask as shown in Fig. 1.

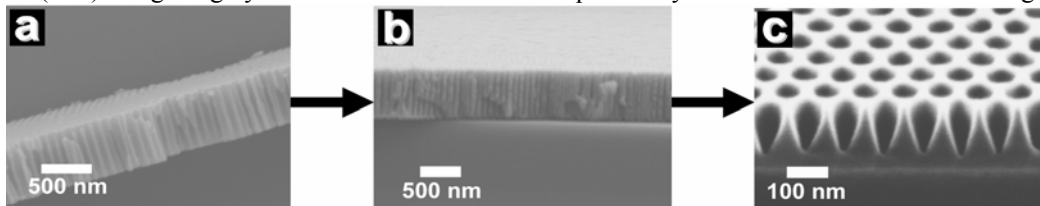


Fig. 1. (a) SEM image of the self-assembled anodic aluminum oxide (AAO) nanopore array's side-view. (b) The free-standing AAO mask can be deposited atop the electronic-grade SOI wafer. (c) The periodic nanopore array pattern is transferred to the SOI by using the AAO as an etching mask. The AAO is then removed by sonication.

The anodic aluminum oxide (AAO) nanopore etch mask was placed atop a thin SOI layer which was insulated from the thick silicon substrate by 3 μm of silicon-oxide. The nano patterning was achieved via reactive ion etching (RIE) which introduced nanopores to the silicon, as shown in figure 1c.

2. Lasing at 1.28 μm and room temperature enhanced photoluminescence by phonon-selection rule relaxation

Fig. 2a shows the lasing line at 1.278 μm in the edge-emission of the slab waveguide pumped by a continuous-wave (CW) 514 nm argon-ion laser. Raman, PL, and Photocurrent spectroscopy studies established the underlying mechanism for lasing to be that of a G-center-mediated, phononless, direct recombination. G-centers are bistable point defects associated with an interstitial carbon-substitutional carbon pair approximately 0.17eV below the band edge which allows fast trapping of electrons [4,6]. Nano-patterning creates a densely packed array of Emissive Structural Deformation (ESD) zones in the side-wall region of the nano-holes. The ESD zones are G-center latent and strained, as revealed in the HRTEM analysis shown in Fig. 2(b,c) [5]. In this system, refinement of the structure and measurement set-up has raised the lasing temperature of the nanopatterned silicon from below 30K to above 80K; enhanced photoluminescence at band edge has also been obtained in this system at room temperature.

Based on the Raman, PL, and Photocurrent spectroscopy studies, we propose an ESD model of the underlying mechanism for the enhanced light emission at room temperature and lasing at cryogenic temperature. As illustrated in Fig. 3, three main features of the ESD zones contribute to enhanced light emission and lasing. First, the silicon lattice in the ESD zones, in the nanopore walls, is strained, resulting in a local narrowing of the band gap which promotes funneling of carriers into the ESD zones from the surrounding which was protected during the RIE and thus remains pristine. Second, lattice strain and nano-scale symmetry breaking give rise to spatial phonon localization and the phonon selection rule breaking which enhances carrier capture in the ESD zone via thermal relaxation [7,8]. Third, the low dimensionality of the nano-structural feature near the nanopore surface causes an increase in the local electronic screening length and therefore a local reduction of the dielectric function for the

carriers in the ESD zone which increases the binding energies of the vacancy defect-associated states below the band edge. The presence and the lowering of these states increase the capture rate of electrons by G-centers.

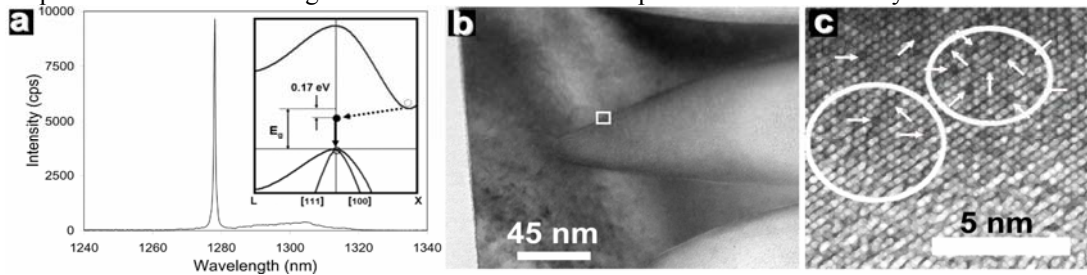


Fig. 2. (a) Edge-emission spectra at 10 K. The inset illustrates the G-center mediated direct recombination pathway between trapped electrons and free holes. (b) Cross-sectional TEM of the nanopatterned SOI structure. The scale bar is 45 nm. (c) High-resolution TEM (HRTEM) of the nanopatterned silicon surface layer region indicated in (b). The arrows indicate vacancy sites in the side-wall of a nano-pore.

Experiments have been conducted to validate the first two components of the model, and it is found that phonon-assisted light emission at the band edge was indeed enhanced at 300K by the nano-patterning, indicating the role of phonon-selection rule breaking [7,8] in the ESD zones. Indeed, Raman, PL, and Photocurrent spectroscopy studies all confirm this effect and show that the ratio of radiative to non-radiative recombination events increased. Moreover, photocurrent spectroscopy clearly reveals the presence of a band tail [5].

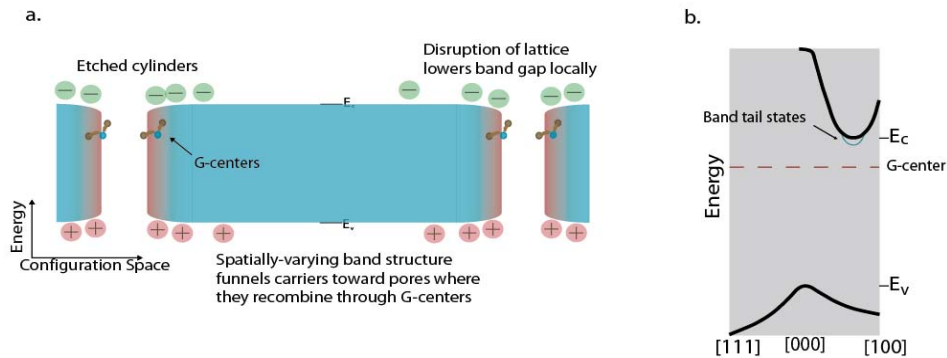


Fig. 3. (a) Schematic of nanopore. The G-centers populate the strained walls. Carriers are pulled to the region of smaller band gap. (b) The band structure of bulk silicon showing the tail of states below the conduction band. Phonon assisted transitions occur from these tail states to the G-centers. The direct optical transitions are from the G-centers to the valence band.

3. Conclusion

Enhanced band edge photoluminescence at 300K and 1.28 μ m laser emission at $T < 100$ K from nano-engineered silicon originating respectively from phonon k -selection rule breaking and dislocation-mediated phononless direct recombination in a densely packed array of Emissive Structural Deformation zones engineered in a SOI wafer are reported. With the breaking of the phonon-selection rule and the creation of G-center latent ESD zones, this nano-engineering approach holds promise for silicon lasers at higher temperatures. Further investigation is necessary to explore the full implications of the ESD zones, including the effects of the modified dielectric tensor function on A-center population and laser emission polarization.

4. References

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