# Germanium-on-Insulator for Group IV Laser and III-V Integration on Silicon


## Abstract

Germanium (Ge) laser on Ge-on-insulator (GOI) shows great promises as the light source in photonic integrated circuits (PICs) for future data communication and sensing applications. In addition, small lattice mismatch between GaAs and Ge also enables hybrid integration of III-V photonics on silicon (Si) platform via a GOI substrate. This thesis is focused on the development of a high quality GOI substrate for photonics integration. A low-threshold Ge nanowire laser structure was fabricated on the GOI substrate, and the GOI substrate was also used for the epitaxial integration of III-V photonics on Si.

Firstly, in order to fabricate a GOI substrate, a Ge layer needs to be grown on a Si wafer and then transferred to an insulator/substrate via wafer bonding. The Ge layer was directly grown on an 8 inch Si (001) substrate (Ge/Si) using a two-step growth method by metal-organic vapour deposition (MOCVD). Due to the large lattice mismatch (~4%) between Ge and Si, the threading dislocation density (TDD) of the Ge buffer on Si was high (TDD ~$1\times10^{8}$ $cm^{-2}$). By introducing a highly arsenic (As)-doped Ge seed layer to the growth steps, the dislocation velocity in Ge was increased, resulting in a low TDD of $5\times10^{6}$ $cm^{-2}$. Then the Ge/Si wafer was bonded to an 8 inch Si (001) wafer with a bonding dielectric layer to form a GOI structure. The investigations on wafer bonding processes, in terms of TDD reduction and thermal bubbles suppression were conducted to obtain a high-quality mechanically-stable GOI substrate for photonics integration.

Secondly, although Ge is a very promising gain material that enables a monolithically integrated light source on Si, it is still very challenging to achieve a low-threshold Ge laser due to its indirect bandgap. In this thesis, a highly strained Ge nanowire laser structure was fabricated on the previously developed GOI substrate. By employing a high uniaxial tensile strain of 1.6 % in the Ge nanowire, direct band transitions were promoted, resulting the reduction in lasing threshold density to ~1.3 kW $cm^{-2}$ at 83 K under optical pumping. An unambiguous multimode lasing action was evidenced by nonlinear threshold behavior in output power and linewidth narrowing as a function of pump power. Additionally, an optical net gain of ~415 $cm^{-1}$ was achieved. These achievements markedly narrow the gap between conventional III–V lasers and group IV lasers, thus opening up new avenues for PICs.

Thirdly, the epitaxial integration of III-V on GOI shows another promising approach for large-scale electronic-photonic integration. Since the GOI substrate resolves the issue of the lattice mismatch between III-V and Si, III-V initiation conditions on Ge surface are essential to the materials quality of III-V epi-layers. A high-quality GaAs buffer grown on Ge was achieved using a high $AsH_3$ partial pressure of 5 mbar to suppress the formation of anti-phase boundaries (APBs), and the root-mean-square (RMS) roughness was reduced below 1 nm. Then, the GaAs/GOI structure was used as a substrate template for the growth of an AlGaInP LED structure on Si. The LED performance on GOI was investigated to explore the possibilities of using GOI for III-V photonics integration.