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# Molecular Beam Epitaxy of InP-based Heterostructures on Silicon Substrates and Membranes

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Epitaxial growth of III-V compound semiconductors on silicon is significant because, if successful, it can greatly simplify heterogeneous integration. It would, for example, enable dense arrays of optical sensors for infrared wavelengths in which the optically active elements are made of III-V materials and the read-out function is accomplished by silicon circuitry.

Generally, there are three hurdles for successful epitaxial growth of III-V materials on silicon: differences in lattice constants, thermal expansion coefficients, and lattice polarity (i.e. polar vs. non-polar). These differences yield a high density of threading dislocations and antiphase domains in the epitaxial films, which drastically reduce the efficiencies and lifetimes of devices made in them. For diodes and detector structures, these dislocations can also contribute to larger reverse-bias currents or dark currents, reducing speeds and sensitivities. Antiphase domains can be suppressed by using silicon substrates tilted by a few degree from the (100) plane towards the (011) plane. Threading dislocations can in principle be reduced by annealing. Additional defects will be generated in the annealing process, as well as during cool down after growth, however, because the thermal expansion coefficients of Si and the III-Vs differ greatly, and this remains a major unsolved issue.

In order to overcome thermal expansion mismatch, we propose growing III-V materials on suspended silicon membranes, as illustrated in Figure 14. If a silicon membrane is much thinner than the epitaxial layer grown on top of it, the membrane, rather than the epitaxial layer, will absorb most of the stress generated in the composite structure during the cool down cycle and during any annealing cycles. It is our expectation that this Epitaxy on Membrane Silicon (EMSi) technique, used in conjunction with our Aligned Pillar Bonding (APB) process, will permit us to integrate III-V optoelectronic

For our work, we have picked InP as the III-V material of interest, and we have first tried to achieve favorable conditions for its molecular beam epitaxial growth on bulk Si. Previous work growing InP on Si has used MOCVD, rather than MBE. Typically, Si substrates mis-oriented 2 to 3 degrees from (100) or (111) orientations have been used, because they were found to yield far better results than (100) substrates with no misorientation. Thick films, in the order of 2 - 4  $\mu\text{m}$  were routinely grown due to the higher growth rate of MOCVD. A thin intermediate layer of GaAs was sometimes used between the InP layer and the silicon substrate.

In our work, we have used (100) silicon substrates without misorientation. The samples were treated in standard RCA cleaning process, with an added final quick hydrofluoric acid dip without rinsing. This leaves the surfaces terminated by hydrogen. Care was taken to minimize the time between the cleaning of the samples and their loading into the MBE system. All the ion gauges were turned off in the chambers where the sample resided. Complete oxide removal and surface cleaning were achieved by using a high temperature catalytic hydrogen cracker. The cracking and substrate temperatures were 2200°C and 630°C, respectively. After one hour of oxide removal process, the surfaces gave strong 2X2 reconstruction as observed by RHEED.

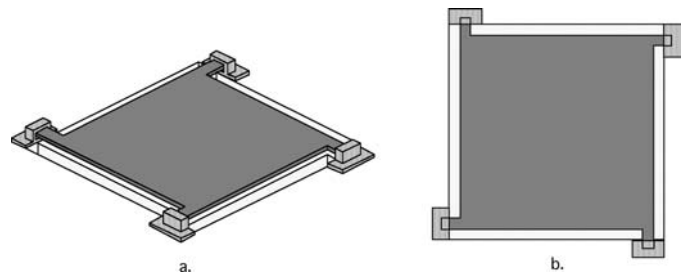


Fig. 14: Perspective (a) and top (b) views of a suspended silicon membrane on an SOI wafer made using MEMS selective etching techniques. The membrane is held at its four corners, and deep trenches are etched along the sides, so the growth on the membrane will be free from the deposition on the edges.

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The growth was done in two steps: First, an initial 100 nm was grown at a slow growth rate of 0.2  $\mu\text{m/hr}$ . Then, a 1  $\mu\text{m}$  layer was deposited at 0.8  $\mu\text{m/hr}$  under conditions we have found to be critical to overall success. In the second layer, all growth parameters are identical to those used in lattice-matched InP on InP growths.

The FWHM of InP X-ray peaks was 300 arcseconds, and the photoluminescence spectrum is comparable to that of InP on InP, 30 times less intense. These results are comparable to the best published results for MOCVD growth of InP on Si, which is particularly encouraging because 1) these results are, to our knowledge, the first ever MBE heteroepitaxial growth of InP on Si, and 2) the films in this study were of much thinner than those in the MOCVD work, and similarly thick films would be expected to give even better results in our case.

We presently are in the process of measuring the threading dislocation density as a function of film thickness, and of investigating the use of GaAs, InP or GaP as intermediate layers between the InP layers and silicon substrates. Preparation of the membrane structures pictured above is also proceeding.

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