Honeycomb Lattice Patterned on GaAs Quantum Well: Artificial Graphene

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The appearance of mass-less Dirac fermions in graphene originates from the linear energy-momentum dispersion of the electronic states in proximity to the K points of the hexagonal Brillouin zone. This unique quantum behavior is a direct result of the honeycomb symmetry of the graphene lattice. The prospect of reproducing this physics in an adjustable, artificial honeycomb lattice offers a platform for the exploration of novel behaviors and new quantum regimes of mass-less Dirac-fermions that would be difficult if not impossible to observe in graphene, due to the inability to tune the lattice parameter, as well as difficulties in manipulating and controlling defects and edges and high magnetic fluxes.

The electronic properties of a 2D electron gas (2DEG) whose density is modulated by a periodic potential with honeycomb symmetry have been predicted to generate mass-less Dirac-fermions with tunable Fermi velocity.[1,2] This system, also known as "artificial graphene" (AG), is implemented in this work in a modulation doped AlGaAs/GaAs quantum well. Modulation of the electron density in the quantum well is accomplished by reactive ion etching of the surface to within a few tens of nanometers from the quantum well using a metal hard mask patterned by electron-beam lithography combined with metal deposition and lift-off in the form of a honeycomb artificial lattice with varying lattice parameters, down to ~ 40 nm. BCl_3-based shallow ICP-RIE of the surface produces cylindrical pillars below which the 2DEG is expected to form quantum dots, where the electron density is higher than in the surrounding etched regions (Fig. 1 and 2).

Previous experiments on larger scale AG (lattice parameter ~ 130 nm) have shown evidence of the Mott-Hubbard physics.[3] These experiments were limited by the relatively large AG lattice parameter which affects the range where the energy band is linear. We have reduced the artificial lattice parameter by a factor of more than three and measured optical transitions attributable to the formation of the AG energy mini-bands (Fig. 3). We expect to be able to explore in more detail the quantum phenomena related to Dirac-fermions thanks to this controllable ultra high-mobility semiconductor system.

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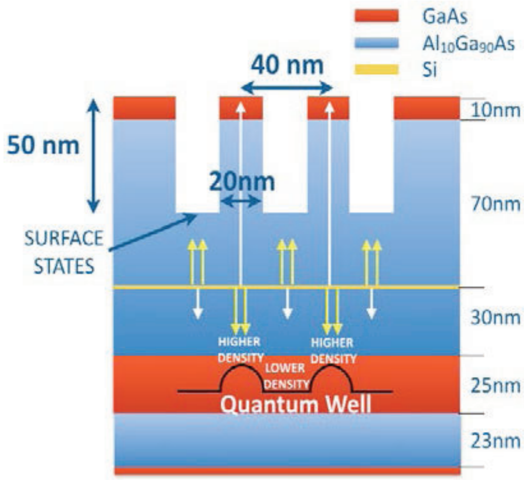

Fig. 1: Schematic of the cross-section of the artificial graphene. The electrons, coming from the Si donors, feel two competing attractions, the first towards the quantum well states and the second towards the surface states. The latter dominates when the surface is closer to the doping layer (etched regions), resulting in a lower electron density in the quantum well.

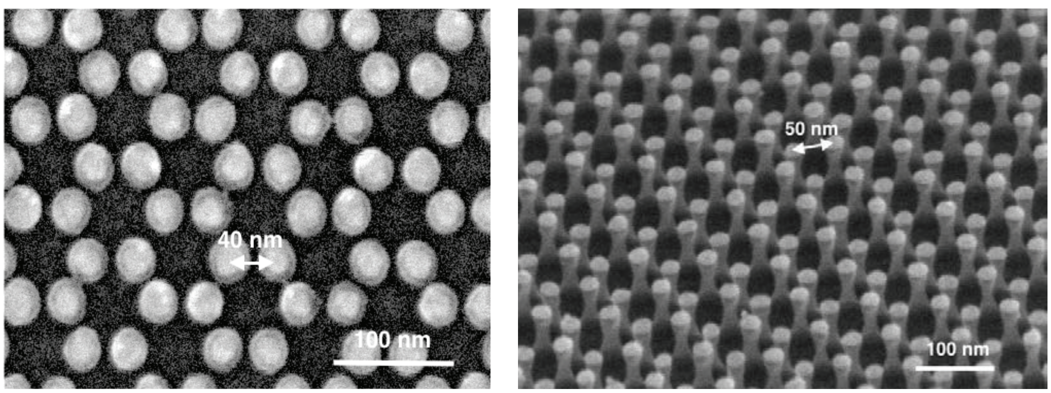

Fig. 2: Left: top view of the honeycomb artificial lattice of metallic disks constituting the mask for the subsequent dry-etching of the substrate. Right: Nano-pillars resulting from the BCl_3-based ICP-RIE of the surface of the substrate. The diameter and height of the pillars as well as the lattice parameter (inter-pillar spacing) can be controlled and varied during the fabrication, allowing tuning of the energy mini-bands.

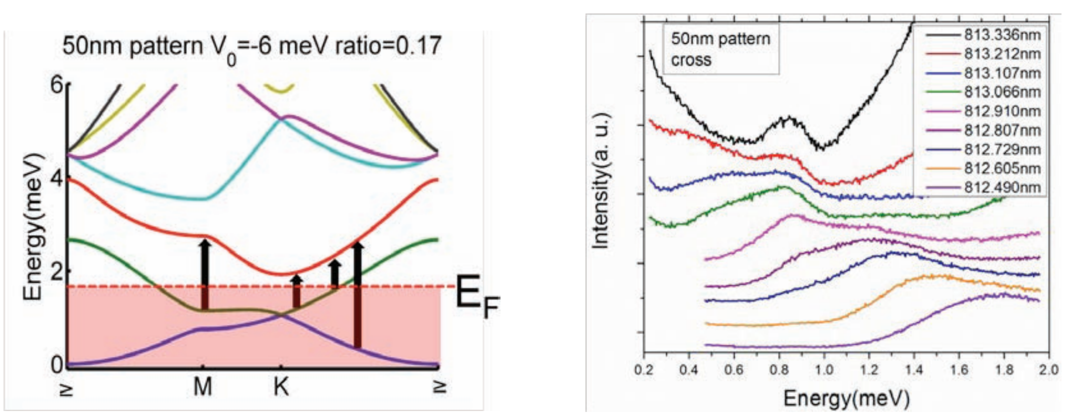

Fig. 3: Preliminary low temperature (4 K) inelastic light scattering data collected from the optical analysis of a 50 nm-pitch artificial graphene. From the simulation of the energy mini-bands (left) using a muffin-tin periodic potential, it is possible to relate the Raman peaks observed in the spectra (right) to inter-mini-band electronic transitions.