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Observation of electron states of small period artificial GaAs graphene in nano-patterned quantum wells

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Engineered honeycomb lattices, called artificial graphene (AG), are tunable platforms for the study of novel electronic states related to Dirac physics. In this work, we report the achievement of AG electron bands in the nano-patterned GaAs quantum wells that are tunable from 40 nm to 25 nm. The AG band structures reveal peaks which are interpreted as combined electronic transitions between subbands of the quantum well confinement with a change in the AG band index. Spectra lineshapes are explained by joint density of states obtained from the calculated AG electron band structures. These results provide a basis for further advancements in AG physics. Published by AIP Publishing.

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Graphene consists of a single layer of carbon atoms arranged in a honeycomb lattice. Charge carriers in graphene have a linear energy-momentum dispersion that has led them to be characterized as massless Dirac fermions (MDFs). The MDFs that result from the symmetry of the lattice should be observable in other systems with a similar topology. Unlike natural graphene, an artificial honeycomb lattice offers tunable parameters such as intersite spacing and coupling that allow for the exploration of the fascinating physics of the electron states associated with the honeycomb topology further than possible in natural graphene. So far, Dirac physics in artificial graphene (AG) potentials have been achieved in molecular and optical lattices. Particularly promising would be the realization of Dirac physics in semiconductor systems, where the nanofabrication methods offer a great design flexibility and easier integration with the optoelectronic components.

Nano-patterned semiconductor quantum well (QW) structures hosting an ultrahigh-mobility two-dimensional electron gas (2DEG), called lateral superlattices, were intensively studied in the late 1980s and 1990s. Creation of superlattices with observable minibands requires extremely low disorder QW, high lattice uniformity, and especially small lattice constant. These requirements impose substantial challenges to the fabrication technologies. Evaluations of electron bands of AG lattices in the nano-patterned semiconductor QWs show that the AG lattice constants required to see that the well-defined AG bands are significantly smaller than those fabricated in this type of system to date.

We recently demonstrated AG lattices in the nano-patterned GaAs QWs with lattice constants as small as 40 nm, which is the current state of the art. We have used these to explore the formation of AG electron bands in small period honeycomb lattices. In this paper, we present evidence of AG electron band structures in such artificial lattices. Evidence of well-defined AG electron bands is found in the resonant inelastic light scattering (RILS) spectra of inter-subband transitions. The spectra reveal peaks which are interpreted as combined electronic transitions between the subbands of the quantum well confinement with a change in the AG band index. Those transitions are well explained by a calculation of the joint density of states (JDOS) in a fashion that reflects the underlying honeycomb lattice topology.

The formation of AG bands in the nano-patterned semiconductor systems creates tunable platforms for the study of AG physics. Dirac cones are expected to be well-developed within the parameter space of our lattices, as seen in our calculations.

Figure 1 describes the method for the realization of AG lattices in a GaAs QW. The fabricated AG lattices are superimposed on a two-dimensional electron gas confined within a 25 nm-wide one-side modulation-doped GaAs/Al0.1Ga0.9As QW (Fig. 1(a)). The QW is positioned 110 nm below the surface and 30 nm below the Si δ-doping layer. The as-grown electron density is 1.8 × 1011 cm−2, with the low-temperature...
Intersubband excitations observed in the RILS spectra offer a powerful method for probing the electron states produced by the AG lattice. Intersubband excitations deriving from the changes in the confinement in the QW are illustrated in the supplementary material (Fig. S1) for the as-grown sample. Collective modes have well-defined polarization selection rules. The single particle excitations at energy 21.8 meV (denoted by $E_{00}$) are independent of the polarization configuration.

The RILS spectra of intersubband excitations of the AG pattern with $a = 40$ nm, shown in Figs. 2(a) and 2(b), display a strong peak at 20.9 meV, denoted by $E_{00}$, accompanied by several weaker satellite peaks. The strong peak $E_{00}$ is present in both polarizations and thus is interpreted as the single particle transition between the first two subbands of the QW confinement. It is red-shifted from $E_{00}$ due to a decrease in the 2DEG electron density after etching. The satellite peaks, only present in the etched AG sample, are interpreted in terms of combined transitions between subbands of QW confinement and electron states created by the periodic potential of the AG lattice, as schematically shown in Fig. 2(c). In these combined transitions, the change in the AG band index provides insight into physics associated with honeycomb topology.

In a simplified description, the RILS spectra in Figs. 2(a) and 2(b) are interpreted as proportional to the JDOS (see supplementary material) for combined intersubband transitions with the AG band index change, such as those shown in Fig. 2(c). The JDOS calculation (Fig. 3) includes different possible transitions in the energy range close to $E_{01}$ and consists of both red-shifted and blue-shifted transitions. The JDOS is broadened by a Gaussian function with full width at half maximum (FWHM) of 0.2 meV. The calculated JDOS is based on the band structures shown in Fig. 2(c) and does not take into account the energy dependence of the RILS matrix element. The parameters in the calculation $r$, $V_0$, and the Fermi energy, $E_F$, are first estimated from the experiments and then adjusted for the best fit of JDOS (see supplementary material). The uncertainties of the parameters for the best fit are: 0.4 nm for $r$, 0.2 meV for $V_0$, and 0.1 meV for $E_F$. The radius of the potential used in modeling, $r$, is smaller than the physical radius of the pillars, $r_0$, indicated in Fig. 1(a). Nevertheless, this simplified model provides a rather good interpretation of the satellite peaks.

To identify the energies of the satellite peaks $E_{01}$, $E_{11}$, and $E_{12}$, we fit the spectra with multiple Lorentzian peaks. The results of the fit are shown in Fig. 3. The calculated JDOS has the maxima at energies that overlap with those of the satellite peaks. The strong peak of JDOS at $E_{01}$ (lowest panel in Fig. 3) arises from transitions between the subbands with the same AG band index (such as transitions from $c_{01}$ to $c_{10}$ and from $c_{01}$ to $c_{11}$ in Fig. 2(c)), which involves parallel bands with a high JDOS. The red-shifted satellites $E_{01}^R$ and $E_{11}^R$ arise from transitions between $c_{01}$ and $c_{10}$, while the blue-shifted satellites $E_{01}^B$ and $E_{11}^B$ from transitions between $c_{01}$ and $c_{12}$. The shaded area $E_{01}^R$ of the JDOS in Fig. 3 overlaps the RILS signal seen at lower energies in the top spectrum of Fig. 2(a).

Results from the pattern with $a = 50$ nm are shown in Fig. 4. The red-shifted peak $E_{12}^R$ is resolved at lower incident
photon energy, while the blue-shifted peak $E^{1,2}_B$ is resolved at higher photon energy. The smaller energy scale here, due to the larger lattice constant, results in the more narrowly spaced features in the JDOS and single broader RILS satellite peaks $E^{1,2}_R$ and $E^{1,2}_B$ rather than separate peaks seen for the $a = 40 \text{ nm}$ pattern (Fig. 3). The results clearly demonstrate the impact of the lattice constant on the AG band structures.

Intersubband excitations from near the Dirac point are currently not resolved due to their overlap with the strong main peak $E_{01}$ of the RILS spectra. We estimate the linear dispersion range of the AG band structures to be about 0.5 meV for parameters used for the $a = 40 \text{ nm}$ pattern (Fig. 2(c)), large enough to be observed in the future using optical spectroscopy. The Fermi energy of AG lattices could additionally be controlled by gating, to provide access to transitions involving Dirac cones of the band structures.

In conclusion, we have found evidence of well-formed AG bands in a modulation-doped AlGaAs/GaAs QW patterned with small period honeycomb lattices. The RILS spectra reveal combined transitions with a simultaneous change of the AG band index and subband index that manifest as satellite peaks. This interpretation is well supported by the calculation of the JDOS. The fitted AG electron energy band structures suggest the presence of well-developed Dirac cones which future experiments should be able to access.
When the Fermi level is placed around the Dirac cone in the presence of a magnetic field, a $\sqrt{B}$ dispersion\textsuperscript{23–25} of inter-Landau level transitions can provide further evidence of Dirac fermions. The realization of the AG lattices in a nano-fabricated high-mobility semiconductor system offers the advantage of tunability through the methods suitable for device scalability and integration. The implementation of such an AG lattice in materials with strong spin-orbit coupling should enable the exploration of topological insulating states with great tunability.\textsuperscript{26,27}

See supplementary material for intersubband excitations of the as-grown sample, definition of JDOS, and estimation of parameters for modeling.

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\textsuperscript{16}In order to have a Dirac cone with linear dispersion range of about 0.5 meV, the distance between two pillars in honeycomb lattice need to be about 40 nm.

\textsuperscript{17}G. De Simoni, A. Singhia, M. Gibertini, B. Karmakar, M. Polini, V. Piazza, L. N. Pfeiffer, K. W. West, F. Beltram, and V. Pellegrini, Appl. Phys. Lett. \textbf{97}, 132113 (2010).


\textsuperscript{22}The FWHM of broadening used here (0.2 meV) considers the spectrometer resolution in RILS (0.1 meV) and the variation of diameter of pillars.


\textsuperscript{27}Following Ref. 26, a band gap of 0.4 meV can be opened around Dirac points with lattice constant $L = 40$ nm on nano-patterned p-type GaAs QWs.