Transport Anisotropy in One-dimensional Graphene Superlattice in the High Kronig-Penney Potential Limit

Tianlin Li,[1] Hanying Chen,[1] Kun Wang,[1] Yifei Hao,[1] Le Zhang,[1] Kenji Watanabe,[2] Takashi Taniguchi,[3] Xia Hong[1†]

[1] *Department of Physics and Astronomy University of Nebraska, Lincoln, Nebraska, USA*
[2] *Research Center for Electronic and Optical Materials, National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan*
[3] *Research Center for Materials Nanoarchitectonics, National Institute for Materials Science, 1-1 Namiki, Tsukuba 305-0044, Japan*

One-dimensional (1D) graphene superlattice (GSL) has drawn considerable research interest as it is promising for realizing the electron lensing effect [1]. Despite the intensive theoretical studies, 1D GSL has only been realized experimentally via periodic dielectric gates in previous studies [2, 3], which yields a moderate Kronig-Penney (KP) potential profile that is not viable to achieve electron supercollimation.

In this work, we demonstrate 1D GSL in the high KP potential limit exploiting nanoscale domains patterning in a ferroelectric bottom gate [4]. We work with 50 nm (001) $PbZr_{0.2}Ti_{0.8}O_3$ (PZT) films deposited on 10 nm $La_{0.67}Sr_{0.33}MnO_3$ buffered $SrTiO_3$ substrates. Monolayer graphene field-effect transistors with top h-BN global gates are fabricated on PZT prepatterned with periodic polarization up (P_{up}) and down (P_{down}) stripe domains, with the period L varying from 200 to 300 nm (Fig. 1a). The polarization shifts the Fermi level of graphene, leading to a KP potential V_0 of about 0.9 eV at 2 K. We fabricate 1D GSL samples in two configurations, with current along the SL vector $\hat{s}$ and perpendicular to $\hat{s}$. For the former samples, additional Dirac points (DP) emerge in the sheet resistance (R_{xx}) *vs.* top-gated induced electron doping δn (Fig. 1b), from which emanates multiple Landau fan branches in the magnetic field (Fig. 1c). This feature is absent in the latter configuration (R_{yy}), which can be attributed to the SL modulated band crossings along $\hat{s}$. The carrier density between consecutive DP positions (Δn_{DP}) scales with the SL period as $\Delta n_{DP} \propto L^{\beta}$, with $\beta = -1.18 \pm 0.06$ (Fig. 1d), which closely resembles the inversely proportional relation predicted for the high KP potential limit. Figure 1e shows the simulated 1D GSL band structure for our ferroelectric doping scheme, with dimensionless KP potential $u = \frac{V_0 L}{\hbar v_F} = 90\pi$, which reveals a highly flattened band that can potentially host electron lensing effect.

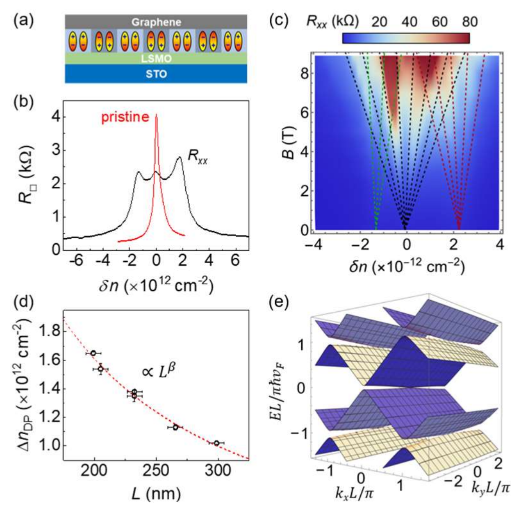

Figure 1. (a) Schematic of 1D GSL. (b) $R_{xx}(\delta n)$ of a 1D GSL at 2 K with L = 205 nm. (c) R_{xx} *vs.* n and B for a 1D GSL, with the modeled Landau fans (dashed lines). (d) $\Delta n_{DP}(L)$ for six 1D GSL samples with a fit. (e) Simulated energy band for $u = 90\pi$.

[1] C. H. Park, et al., Nano Letters **8**, 2920 (2008)
[2] S. Dubey, et al., Nano Letters **13**, 3990 (2013)
[3] Y. Li, et al., Nature Nanotechnology **16**, 525 (2021)
[4] T. Li, et al., arXiv: 2309.04931 (2023)

† Author for correspondence: xia.hong@unl.edu

Supplementary Information

1. Periodic Stripe Domains Writing and Device Fabrication

We define Cr/Au electrodes in the four-point measurement configuration on the PZT films and pattern 100 nm wide P_{down} stripe domains spaced by 100-200 nm in a uniformly polarized P_{up} background between the two voltage probes. Figure S1a shows the piezoresponse force microscopy (PFM) image of a stripe domain region with L = 205 nm. The h-BN/graphene stacks are then transferred onto the SL regions (Fig. S1b) followed by Cr/Au deposition on h-BN as the global top-gate electrode.

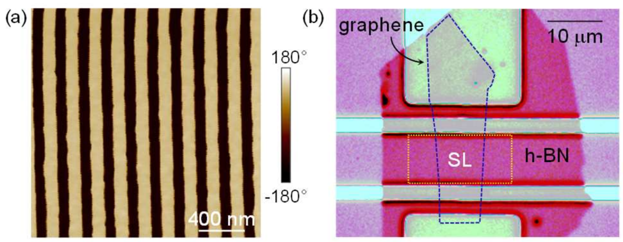

FIG. S1 (a) PFM phase image of strip domains on PZT with L = 205 nm. (b) Optical image of h-BN/graphene transferred on prepatterned domain structure of PZT. The dashed (dotted) lines highlight the boundary of graphene (SL region).

2. Magnetotransport with Current Perpendicular to SL Vector

For 1D GSL with current perpendicular to SL vector $\hat{s}$, the sheet resistance (R_{yy}) exhibits a single peak as a function of top-gate doping (Fig. S2a) with one set of Landau fan branch evolving at high magnetic field (Fig. S2b). This resembles that of pristine graphene, which can be attributed to the suppressed Klein tunneling along the stripe domains and the absence of band crossing perpendicular to the SL vector direction.

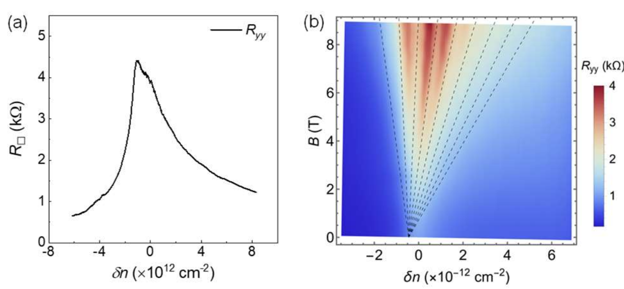

FIG. S2. (a) $R_{yy}(\delta n)$ for a 1D GSL with L = 199 nm, and (b) R_{yy} *vs.* n and B with the modeled Landau fan (dashed lines).

3. Band Flattening at High KP Potential

Figure S3 shows the simulated energy contour plot of the conduction band of 1D GSL with dimensionless KP potential $u = 90\pi$, corresponding to the band structure shown in Fig. 1e. The isopotential contours resemble rectangles, revealing a highly flattened dispersion along k_y, with a Fermi velocity v_y quenched to about 1% of that for pristine graphene.

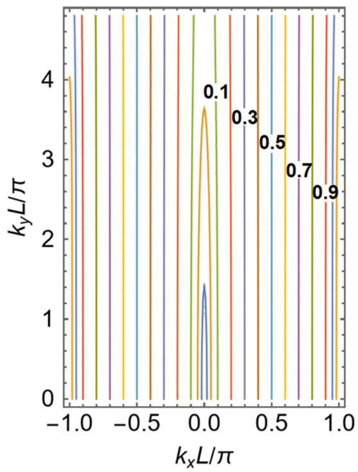

FIG. S3. Energy contour plot of conduction band calculated for the 1D GSL with $L = 200$ nm and $V_0 = 0.9$ eV. The contour lines are evenly spaced with dimensionless energy value $EL/\hbar v_F$ labeled.