Acoustoelectric Probing of Fractal Energy Spectra in Graphene/hBN Moiré Superlattices

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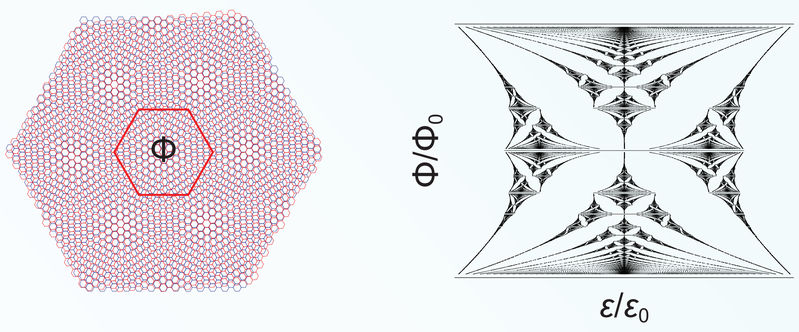
Abstract

Moiré superlattices (SL) with long-range periodicity exhibit Hofstadter energy spectra under accessible magnetic fields, enabling the exploration of emergent quantum phenomena through a hierarchy of fractal states. However, higher-order features, located at elevated energies with narrow bandwidths, typically require high carrier densities and remain difficult to resolve using conventional electrical transport due to limited sensitivity and strong background conductivity. Here, we utilize acoustoelectric (AE) transport to probe high-order fractal states and the Hofstadter spectrum in graphene/hBN moiré superlattices. Surface acoustic waves (SAWs) on $LiNbO_3$ substrate generate an AE voltage proportional to the derivative of electrical conductivity, enhancing the sensitivity to weak spectral features. We resolve Brown-Zak oscillations up to the fifth order and present the first AE observation of the Hofstadter butterfly, revealing high-order fractal Bloch states and symmetry-broken Landau levels over a wide carrier density range. Our results establish AE transport as a powerful probe for emergent fractal quantum states in moiré 2D systems.

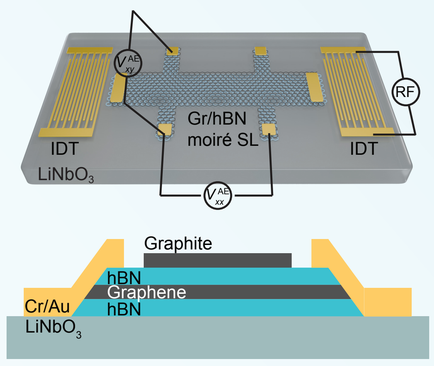
Integration of Gr/hBN moiré superlattice with SAW

Moiré superlattice and Hofstadter's butterfly



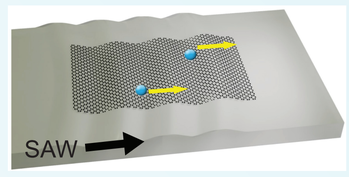
- Fractal energy spectrum in moiré superlattice

Device Structure



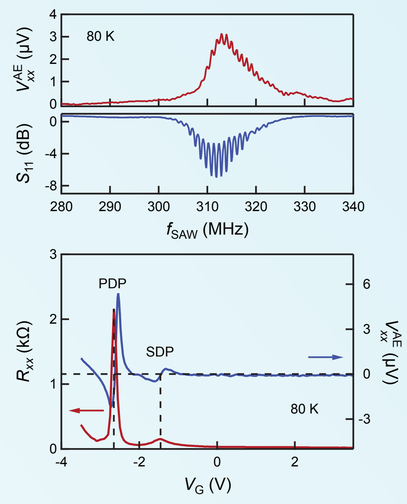
- Gr/hBN moiré superlattice on $LiNbO_3$ substrate

Acoustoelectric effect



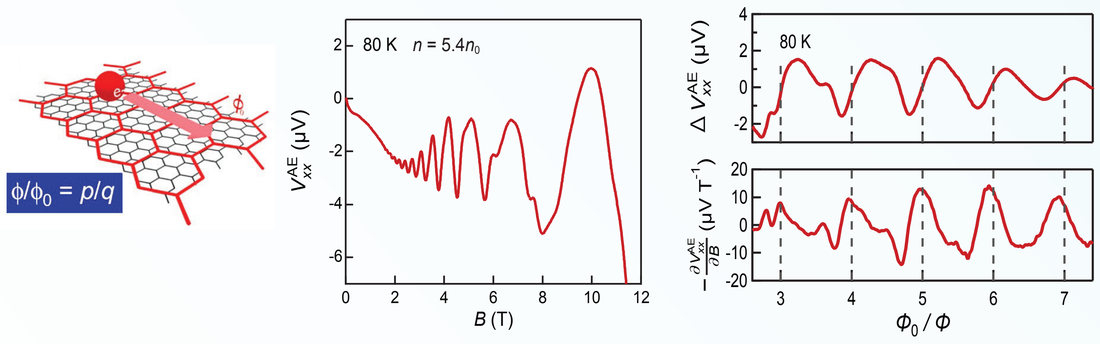
$$j_{\mathrm{d.c.}}^{\mathrm{AE}} = \frac{\Gamma_{\mathrm{SAW}}}{e v_{\mathrm{SAW}}} \left.\frac{\partial \sigma_{xx}}{\partial n}\right|_{\varepsilon_F}$$

- Derivative sensitivity

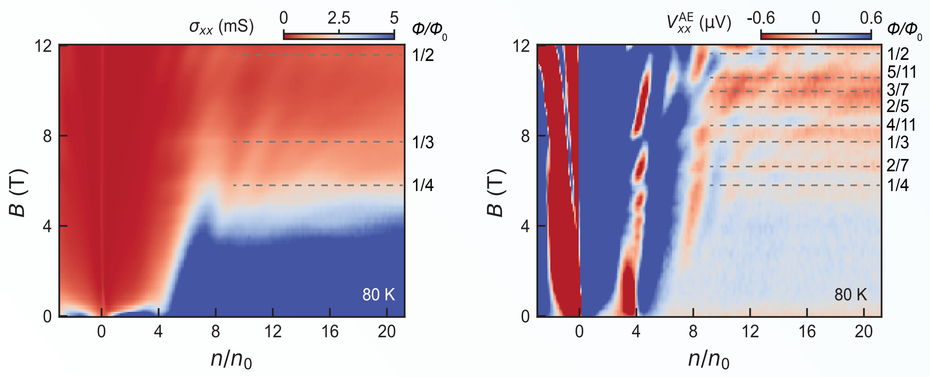


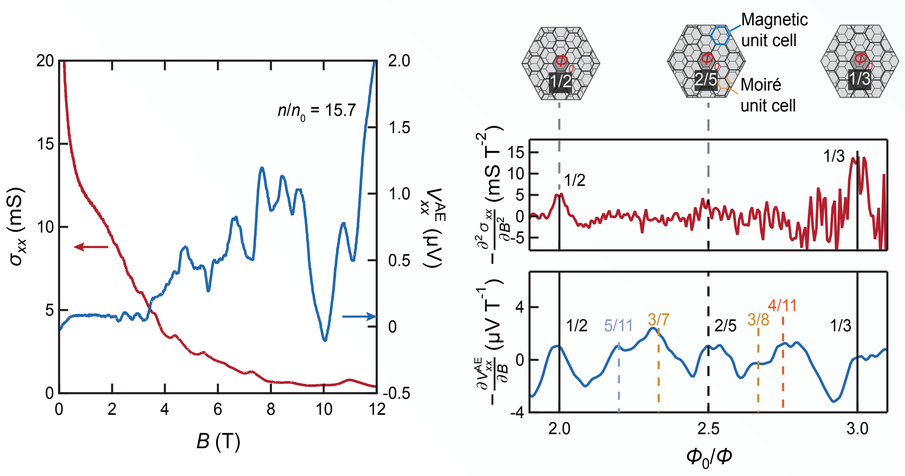
Fractal quantum oscillations by AE

Brown-Zak (BZ) oscillations



High-order fractal BZ oscillations resolved by AE transport

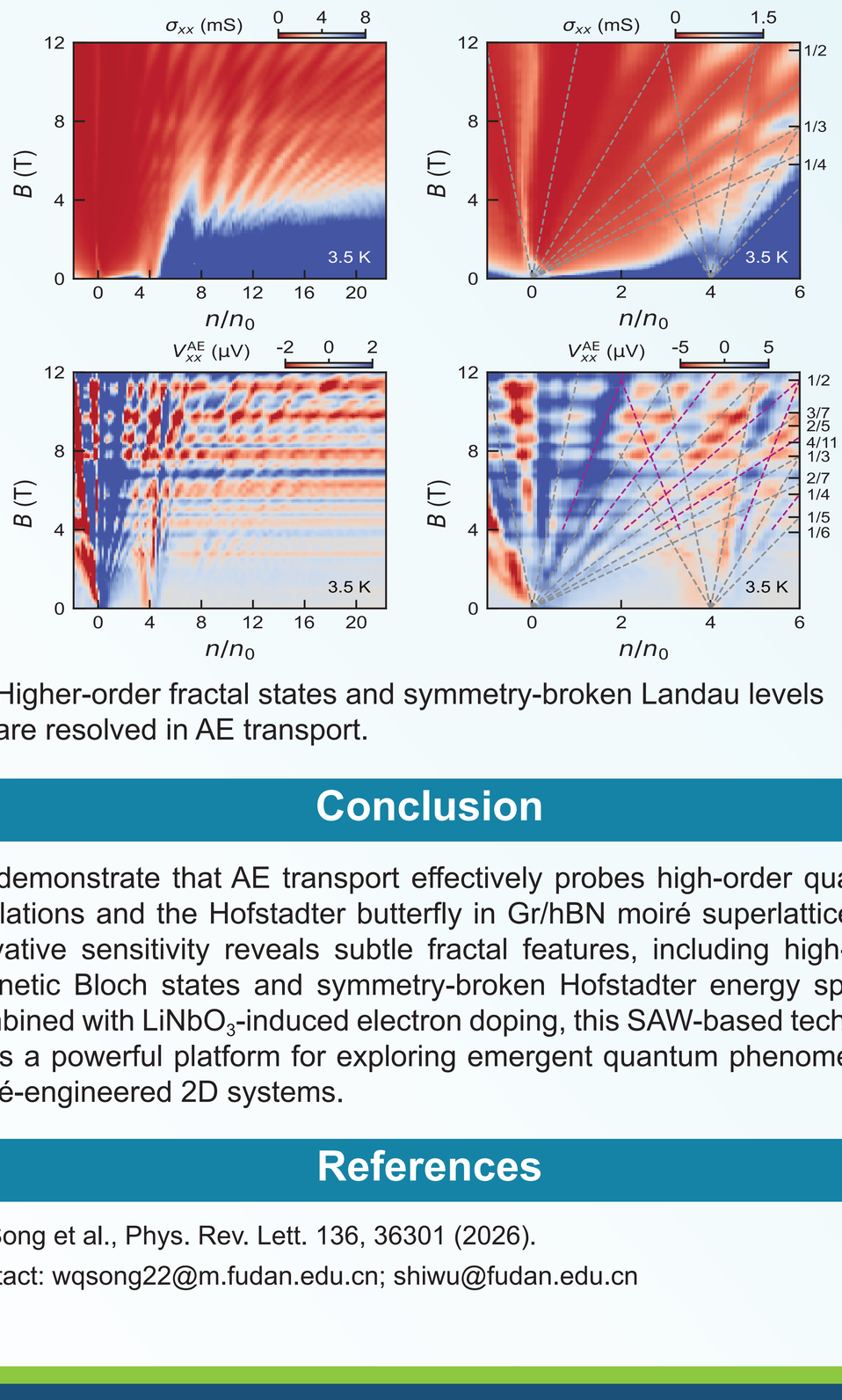




- Derivative sensitivity of AE transport enables the observation of fractal BZ oscillations up to the 5th order.

AE observation of Hofstadter butterfly

Comparison between AE and electrical transport



- Higher-order fractal states and symmetry-broken Landau levels are resolved in AE transport.

Conclusion

We demonstrate that AE transport effectively probes high-order quantum oscillations and the Hofstadter butterfly in Gr/hBN moiré superlattices. Its derivative sensitivity reveals subtle fractal features, including high-order magnetic Bloch states and symmetry-broken Hofstadter energy spectra. Combined with $LiNbO_3$-induced electron doping, this SAW-based technique offers a powerful platform for exploring emergent quantum phenomena in moiré-engineered 2D systems.

References

W. Song et al., Phys. Rev. Lett. 136, 36301 (2026).

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