Piezoelectricity in single-molecular-layer transition metal dichalcogenide

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Background

Piezoelectricity: definition

Application: Resonator & Motor
(electricity to strain)

Measure in-plane piezoelectricity

We combined a laterally applied electric field and nano-indentation in an atomic force microscope (AFM) to measure the in-plane piezoelectrically generated membrane stress. Suspending MoS2 minimized substrate effects such as doping and parasitic charges. The two electrodes were oppositely biased relative to substrate to reduce electrostatic force. The actual frequency was kept much lower than the mechanical resonance and quasi-static analysis is applicable.

Angular & layer dependence

Due to its 3-fold symmetry the piezoelectric coupling of the MoS2 monolayer is:

\( \varepsilon_{33} = -\varepsilon_{11} \)

The change of sign from the upper devices to the lower ones allowed us to assign the atomic orientation, i.e. differentiating the crystal with its mirror image. We also measured the thickness dependence of the piezoelectric coefficient from natural 2H-MoS2 crystals. For even-layer membranes, the contributions to piezoelectricity from alternating orientations of adjacent layers cancelled. That’s why bulk 2H-MoS2 is not piezoelectric.

Out-of-plane piezoelectricity

Many piezoelectric NEMS designs rely on out-of-plane electromechanical coupling. However MoS2, has out-of-plane mirror symmetry and no piezoelectricity along z-axis. We engineered a physical-chemical process to selectively replace the sulfur atoms on one side with selenium and created structural asymmetry.

Results

Transition-metal dichalcogenides, such as MoS2 can retain their structural asymmetry down to the single-layer limit without lattice reconstruction under ambient condition, that enables two dimensional piezoelectricity. The membrane has a total thickness of 0.6 nm and is biocompatible for device applications.

Device fabrication

MoS2 monolayer was produced by mechanical exfoliation on poly-methyl-methacrylate (PMMA). The electrodes were designed to be parallel to or at 60° with respect to the sharply cleaved edges. Suspension, mechanical clamping and electrical contact were simultaneously achieved by one-step electron-beam lithography (EBL). The MoS2 flake was released by critical point drying.

Material challenge

Rough surface and dangling bonds

Size effect in ferroelectric materials

What is the ultimate scale limit of piezoelectric devices? For traditional materials it is challenging to get high-quality surface for freestanding structures. In addition, when the thickness approaches a single molecular layer, the large surface energy can cause piezoelectric devices to be thermodynamically unstable. Prior to this study, there was no experimental measurement of the intrinsic piezoelectric properties of sub-nanometer crystals.

Measure out-of-plane piezoelectricity

Scanning piezoresponse

The MoSiSe flakes were directly synthesized with ramping driving voltage (black scatter). A linear fit (red curve) gives \( e_{33} = (2.9 \pm 0.5) \times 10^{-10} \) C/m (or d = (2.9 \pm 0.5) pm/V). The values agree well with previous ab initio calculations and experiments.

Other IoT Related Works

Light emitting diode integrated on silicon: Efficient carrier injection and light emission was achieved in heterojunctions of monolayer MoS2 (n-type) and heavily doped (p-type) silicon. (Ye et al., Exciton-dominant electroluminescence from a diode of monolayer MoS2, Appl. Phys. Lett. 104, 193508 (2014).)

Acknowledgement & References

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Light emitting diode: Appling a whispering gallery cavity with a high quality factor and optical confinement, we observe bright excitonic lasing from a monolayer WS2 at visible wavelengths under optical pumping, a major step towards two-dimensional on-chip optoelectronics for optical communication and sensing. (Ye et al., Monolayer excitonic lasing, Nat. Photon. 9, 733–737 (2015).)


Opportunity: layered materials

Scanning piezoresponse

Monolayer laser on silicon: Using a whispering gallery cavity with a high quality factor and optical confinement, we observe bright excitonic lasing from a monolayer WS2 at visible wavelengths under optical pumping, a major step towards two-dimensional on-chip optoelectronics for optical communication and sensing. (Ye et al., Monolayer excitonic lasing, Nat. Photon. 9, 733–737 (2015).)

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