Transferred Large Area Single Crystal MoS$_2$ Field Effect Transistors

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Outline

- Introduction
- CVD growth of MoS$_2$
- Transfer of MoS$_2$ film
- Back-gated MoS$_2$ field-effect transistor
- Summary
Layered structure

- Single MoS$_2$ layers are held together by weak Van der Waals
- Enables exfoliation/transfer of MoS$_2$ layers.

Absence of dangling bond, high thermal stability, high carrier mobility, high strength, high flexibility

Mechanical exfoliation method

- Small flakes (few tens of micron scale) → required CVD growth


Most MoS$_2$ films in literature are grown in furnace using MoO$_3$ and sulfur powder as precursors and show polycrystalline structure.

Unable to grow MoS$_2$ directly on plastic substrates because of high growth temperature.

Issues to investigate

- Continuous single crystalline structure
- Transfer of large area 2D materials
Applications

2D/3D Heterostructure

- Large area single crystalline structure
- Transfer of high quality film

Flexible Applications

- Phone (LG electronics, 2013)
- RFID-tag (http://www.technologyreview.com)
- Wearable device (http://www.wirelessefficiency.com)


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5 nm of Mo layer was sputtered on sapphire substrates

- Sulfurized with MoS$_2$ powder at 1100 °C
  - minimize the nuclei density in order to get single-crystal structure.

- Centimeter scale dimension of large area continuous film was obtained.

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Characteristics of as-grown MoS$_2$ film

- (0002) family diffraction peaks of MoS$_2$
- Six peaks at (10-13) plane of MoS$_2$
- Single crystalline nature
- Intensity ratio of $E_{2g}^1/A_{1g} > 1$
- The film shows space charge transport, and the mobility of 192 cm$^2$/Vs was extracted from I-V curve.

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Transfer of MoS$_2$ film

- High quality large area films transferred to arbitrary substrates, using DI water.
- Simple and clean transfer of wrinkle-free, large-area MoS$_2$
- TLM structures on transferred MoS$_2$ film (scale bar = 100 um)

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Transfer of MoS$_2$ film: XRD spectra

- Similar peak intensities and positions compared to the as-grown sample are shown.
- The quality of the large-area MoS$_2$ film is well maintained after the transfer process.
- Relatively large areas of coherent MoS$_2$ films were transferred.

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A smooth surface morphology (RMS roughness of 1.23 nm) of the transferred MoS$_2$ film, comparable to that of the as-grown film (~1 nm).

The thickness of transferred MoS$_2$ film on SiO$_2$ is approximately 10 nm (~15 layers).

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Similar peak position and peak separations (~25 cm⁻¹) for as-grown and transferred MoS₂ films reveals that transfer process maintains the quality of the film.

The variation of the peak intensity ratio \(E_{2g}^1 : A_{1g}^1 : 1.0 - 1.3\)

The film is quite uniform across the measured area (100 \(\mu m^2\)).
Current-voltage (I-V) characteristics in TLM structures on as-grown and transferred MoS$_2$ devices are shown.

Transferred films on sapphire maintain 85% current density and show electron mobility of 98 cm$^2$V$^{-1}$s$^{-1}$. (as-grown MoS$_2$ devices: $\sim$120 cm$^2$V$^{-1}$s$^{-1}$)

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A heavily doped p-type Si wafer with 20-nm-thick SiO$_2$ layer was used as the back-gate.

Ti/Au/Ni metal stack was then deposited as an Ohmic contact, defined using i-line stepper lithography.

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I-V characteristics of MoS$_2$ back gated transistor

- n-channel MOSFET behavior with on/off ratio of $\sim 10^4$.
- Threshold voltage of -0.4 V was extracted by the extrapolation in the linear region.
- Mobility value of 2.4 cm$^2$/Vs was extracted at VDS = 0.1 V.
  - Large current reduction
  - SiO$_2$ is impacting transport.
Interface trap density of MoS$_2$ FETs

- Estimated charge density of transferred MoS$_2$ film at $V_{GS} = 0$V
  - $n_{2D} = C_{OX} (V_{GS} - V_T) \approx 4.3 \times 10^{11}$ cm$^{-2}$
  - As-grown MoS$_2$ film: $\sim 2 \times 10^{11}$ cm$^{-2}$

- Subthreshold slope of 1.45 V/decade and Interface trap density of $\sim 2.5 \times 10^{13}$ eV$^{-1}$cm$^{-2}$ was obtained using the expression, $SS = (1 + qD_{it}/C_{OX})kT/q$.

- Interface traps are from dangling bonds of 3D crystal surface

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First demonstration of transferred centimeter-scale, single-crystalline, few-layer MoS$_2$

Simple and clean transfer of wrinkle-free MoS$_2$ films using DI water

85% current density was maintained after transfer, with a space charge mobility of 98 cm$^2$V$^{-1}$s$^{-1}$

MoS$_2$ field effect transistors (FETs) transferred onto SiO$_2$/Si substrates, with a field-effect mobility of 2.4 cm$^2$V$^{-1}$s$^{-1}$

Interface effects need to be investigated