The Effect of Substrate on the Electron Transport Properties of MoS_2 Field-Effect Transistors

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Outline

Introduction and Motivation

Experimental details

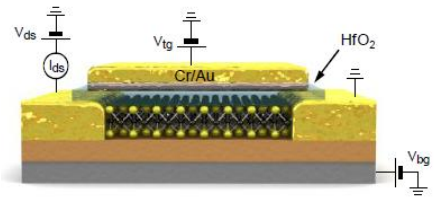
Results

Conclusion

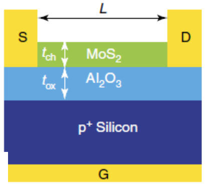
Introduction

Reported mobility of MoS_2

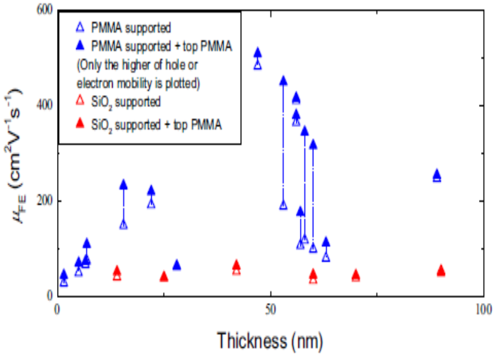
Kis and co-worker reported mobility improvement from ~ 10 $cm^2V^{-1}s^{-1}$ to ~ 60 $cm^2V^{-1}s^{-1}$ at 240 K with high–k dielectric for monolyer MoS_2. (Nature Materials 12, 815–820 (2013))



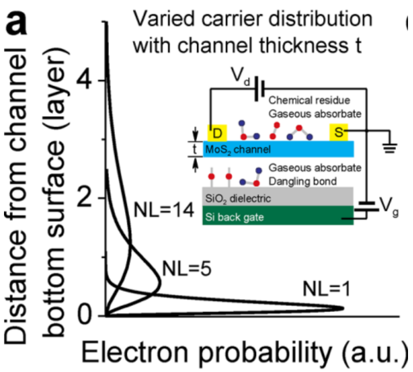
S. Kim et.al. reported multilayer MoS_2 FET on Al_2O_3 with mobility 100 $cm^2V^{-1}s^{-1}$. (*Nat. Commun. 3:1011 doi: 10.1038/ncomms2018 (2012)*)



Bao at. al. reported field-effect mobility of 470 $cm^2V^{-1}s^{-1}$ in ambipolar multilayer MoS_2 at room temperature on PMMA.(*Appl. Phys. Lett.* ***2013, 102,*** 042104.)



S. L. Li et.al. reported thickness dependent RT mobility up to 180 $cm^2V^{-1}s^{-1}$ due to the thickness dependence interfacial charge scattering of MoS_2 FET. (Nano Lett. 2013, 13, 3546−3552)



Phonon limited RT μ is 410 $cm^2V^{-1}s^{-1}$ according to Kaasbjerg et. Al. (*Phys. Rev. B* ***85, 115317, (2012))***

Introduction

Intrinsic scattering mechanism

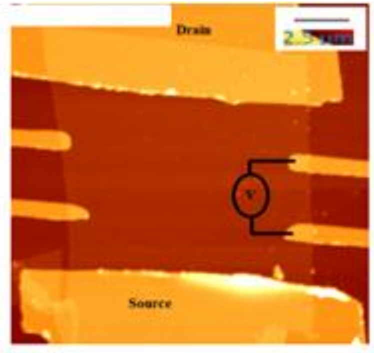
- Optical phonons (> 100 K)
- Acoustic phonons

Extrinsic scattering mechanisms

- Charged impurities at the interfaces and in the substrate/dielectric
- Remote surface optical phonons
- Interface roughness
- Defects in the channel material

~60nm Al_2O_3 on Si/SiO_2

•ALD deposit Al_2O_3 and transfer MoS_2



~290 nm clean SiO_2

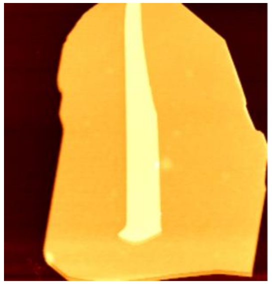
OTMS SAM treated SiO_2

•Si/SiO_2 substrates were modified with OTMS SAM to remove the water adsorbed on surface (hydrophobic).

•Transferred Mechanically exfoliate MoS_2

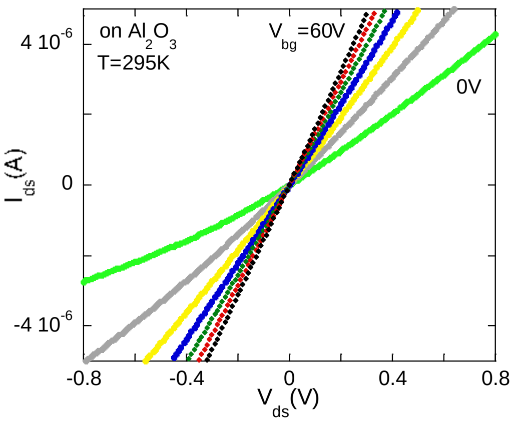
hBN

•Exfoliated MoS_2 on PDMS and transfer MoS_2 on hBN

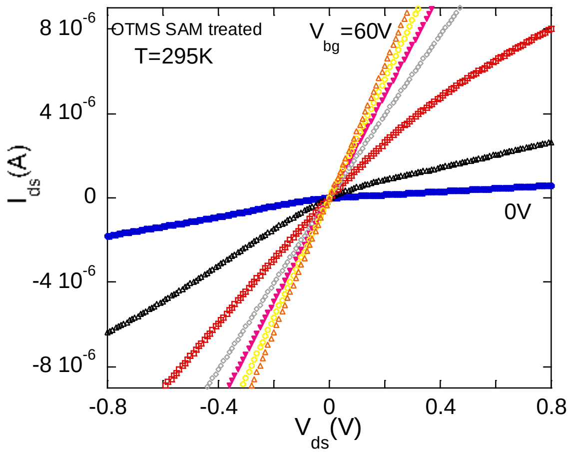


- Selected 3 -12nm thick MoS_2 samples
- 4-probe measurement to exclude contact resistance
- Ti/Au contacts
- Measured in high vacuum
- Back gate

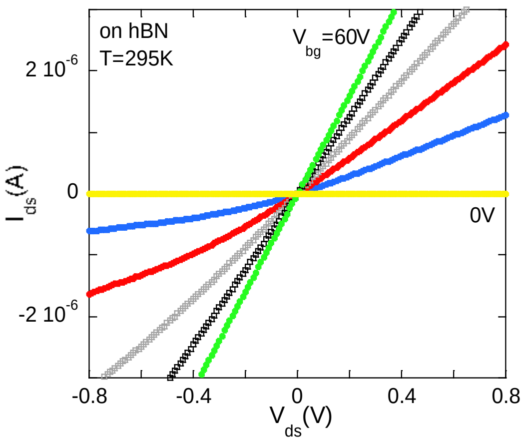
~60nm Al_2O_3 on Si/SiO_2



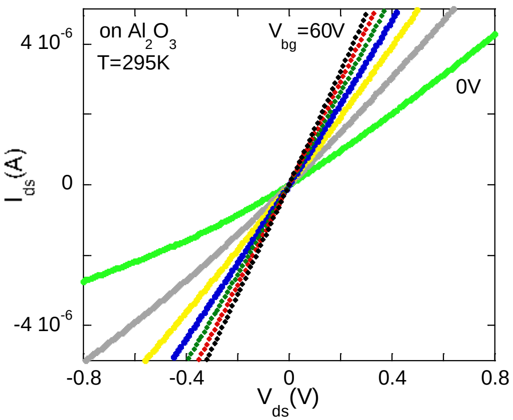
OTMS SAM treated Si/SiO_2

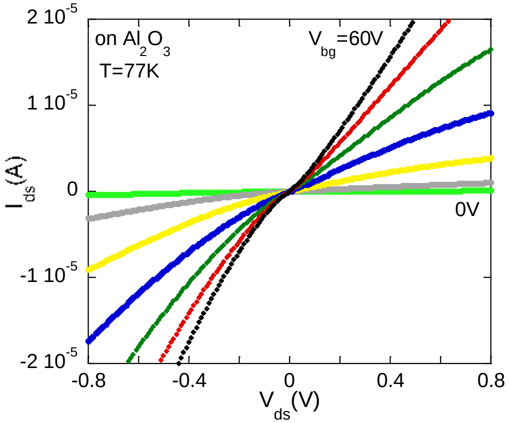


hBN

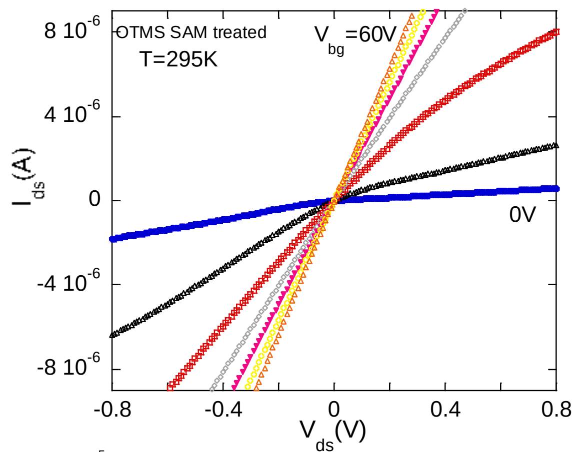


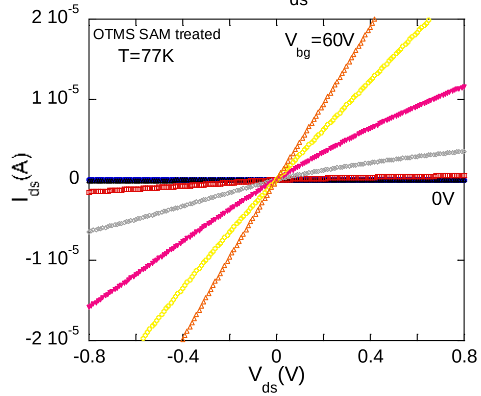
~60nm Al_2O_3 on Si/SiO_2



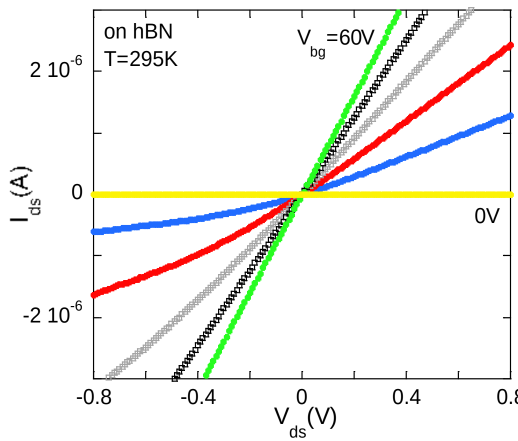


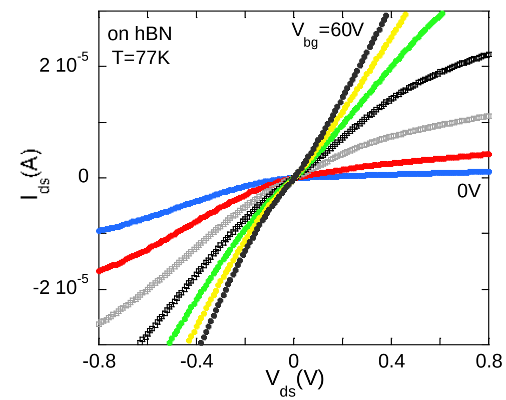
OTMS SAM treated Si/SiO_2



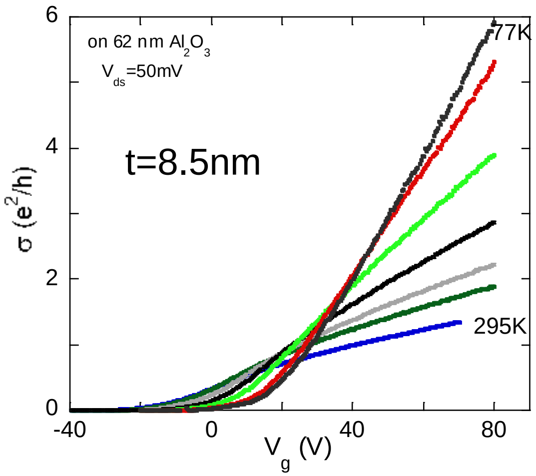


hBN

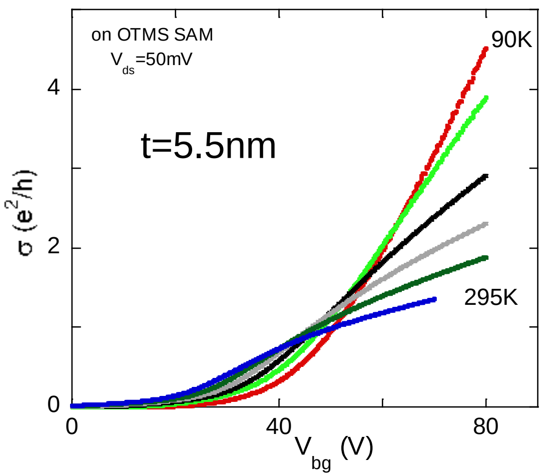




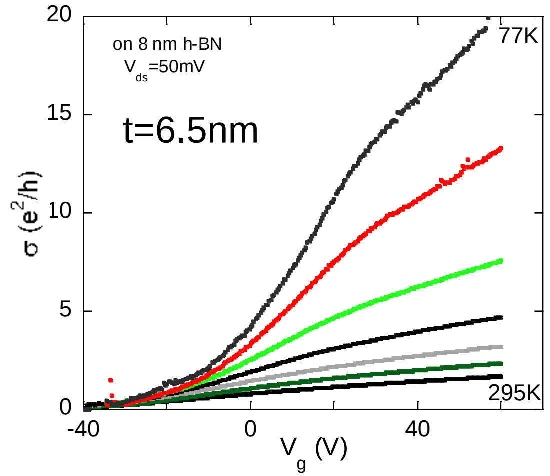
~60nm Al_2O_3 on Si/SiO_2



OTMS SAM treated Si/SiO_2



hBN



- Results on Al_2O_3 and OTMS SAM treated SiO_2 are similar to MoS_2 on clean SiO_2
- Metal-insulation transition (MIT) on all substrates but **absent on hBN**
- Non-metallic behavior likely due to carrier localization induced by charged impurities in the substrate and at the interface
- Absence of MIT on hBN indicates reduced charged impurities and adsorbates

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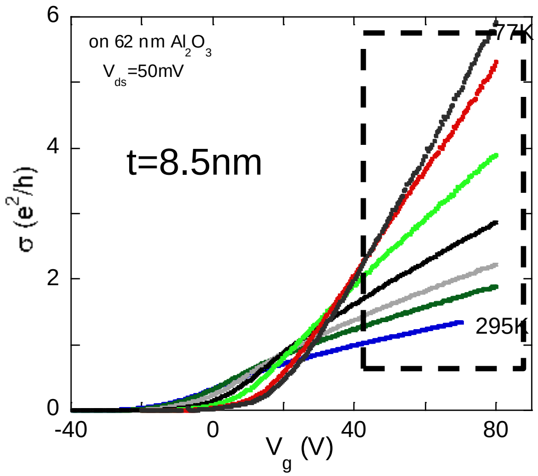
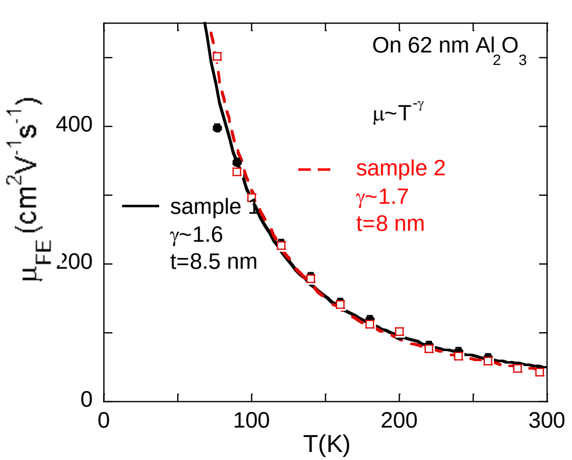
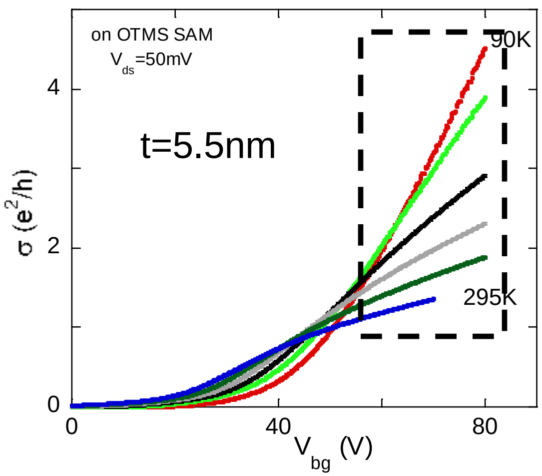
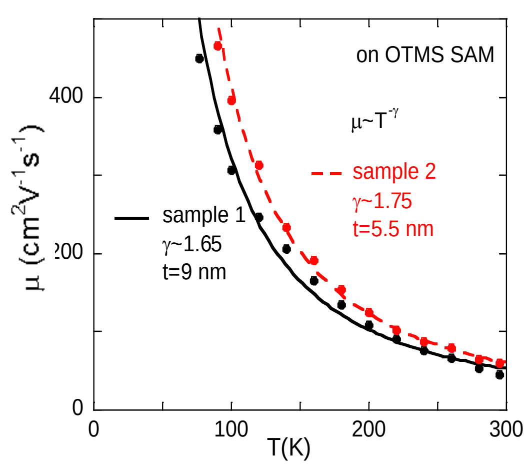
~60nm Al_2O_3 on Si/SiO_2



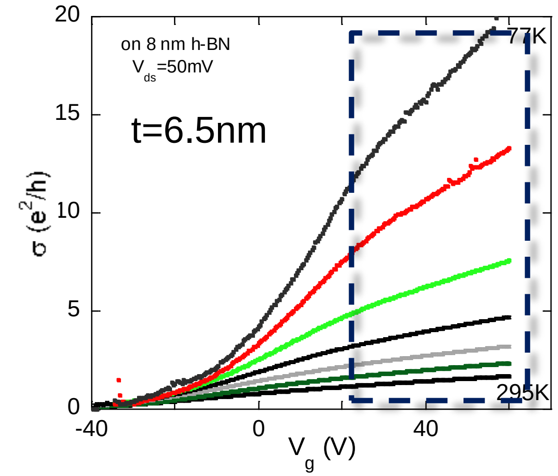


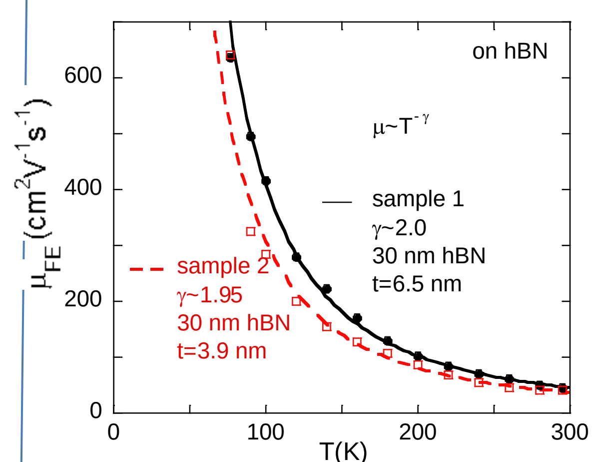
OTMS SAM treated Si/SiO_2





hBN

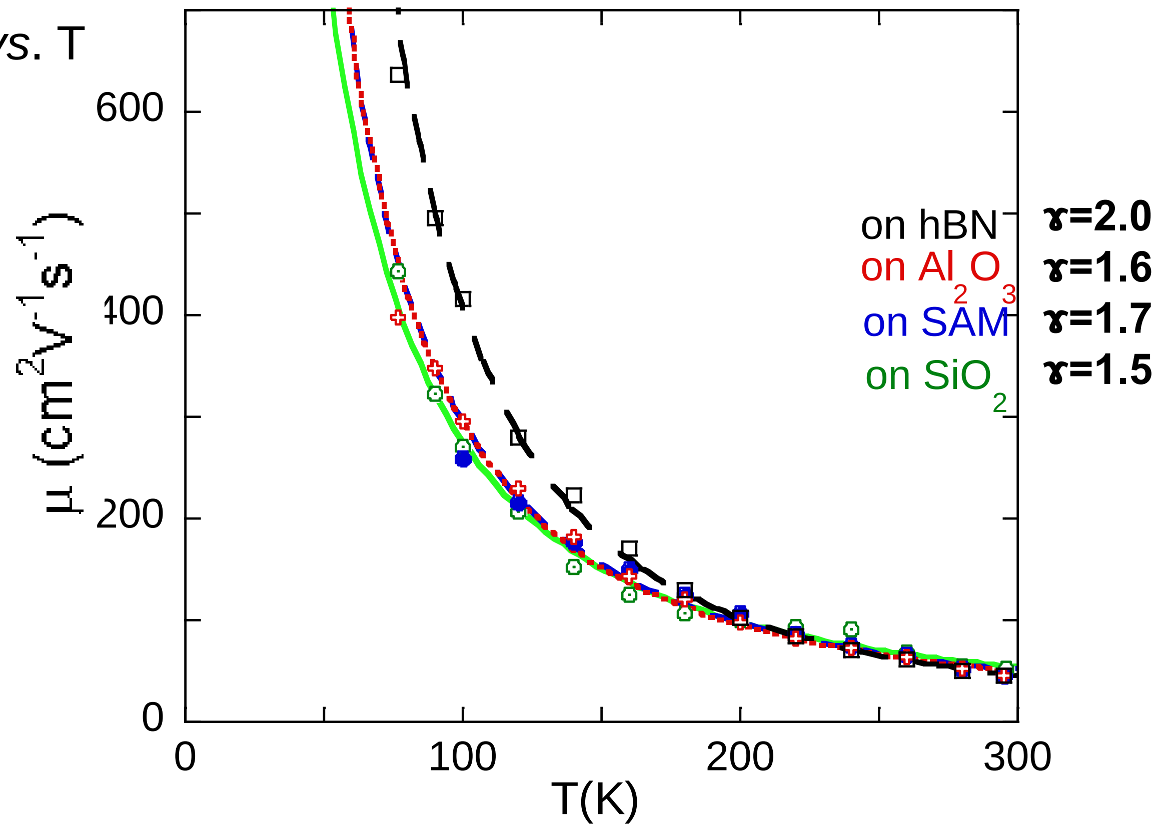




Similar to Xu Cui et. al.
(http://arxiv.org/abs/1412.5977)

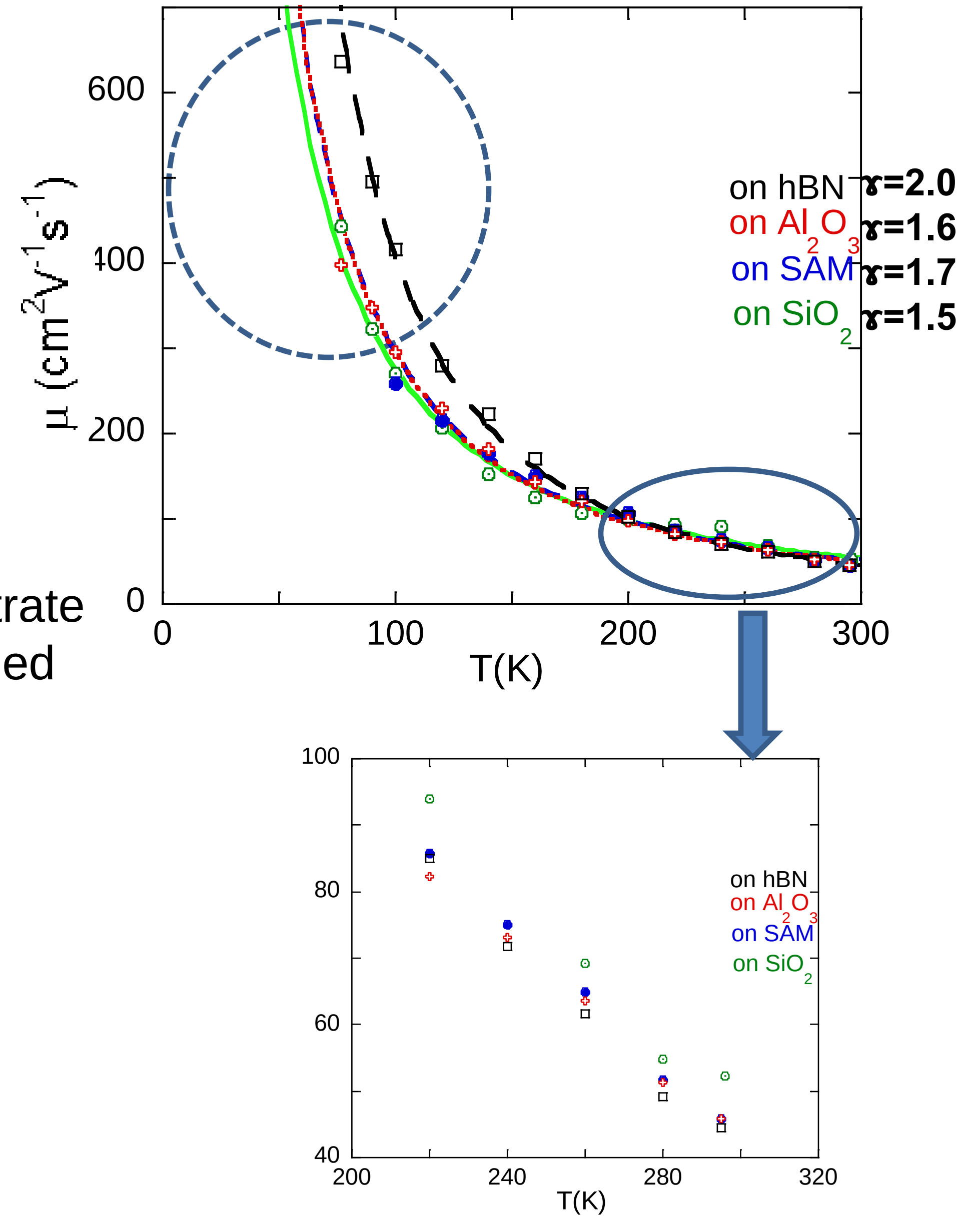
4-probe field-effect mobility *vs*. T on 4 types of substrates:

- hBN
- Al_2O_3
- OTMS SAM
- SiO_2

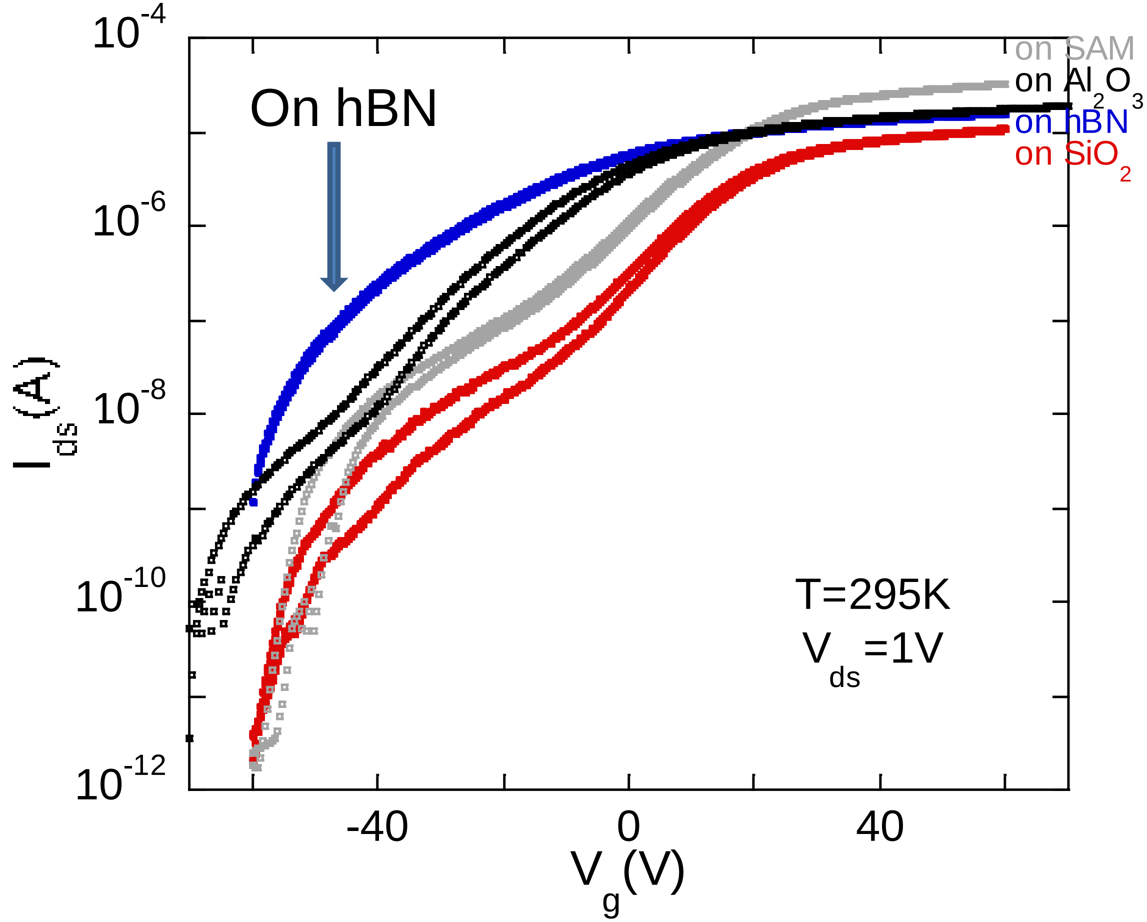


• Higher mobility observed in MoS_2 devices on clean hBN substrates at low temperatures likely due to reduced impurity scattering and smoother surface.

• Mobility of similar value is observed in MoS_2 devices on different substrates at room temperatures
→RT mobility NOT limited by substrate and interface effects such as charged impurity scattering

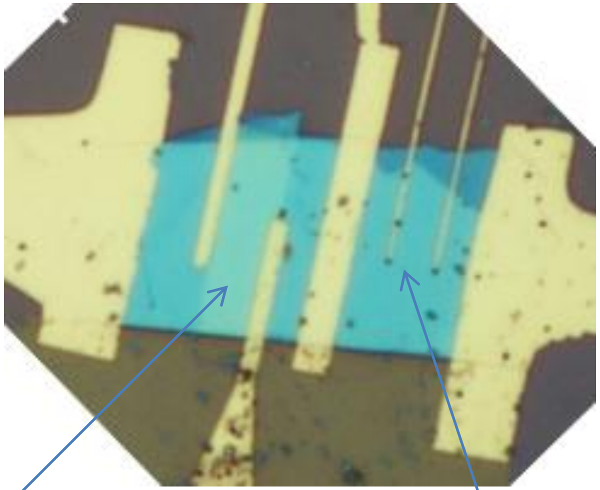


Hysteresis comparison



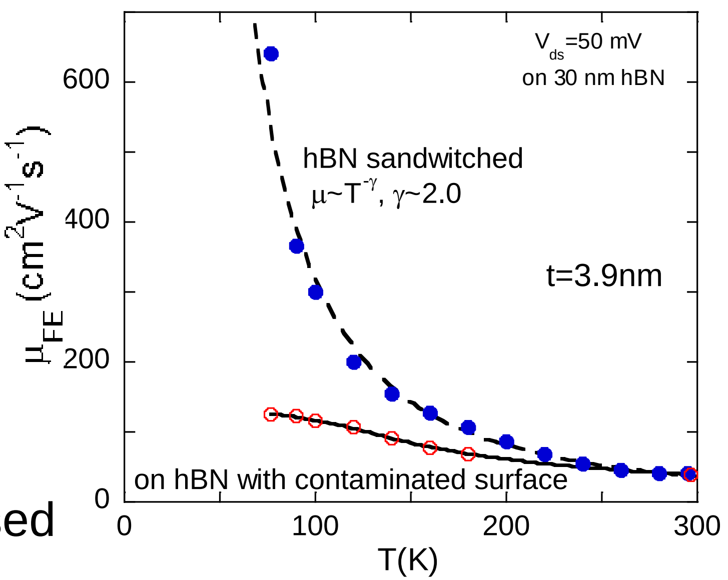
•Smaller hysteresis on hBN substrate → cleaner interface and/or reduced charge traps in the substrate

•Consistent with reduced charge impurity scattering and thus a stronger temperature dependence of the mobility

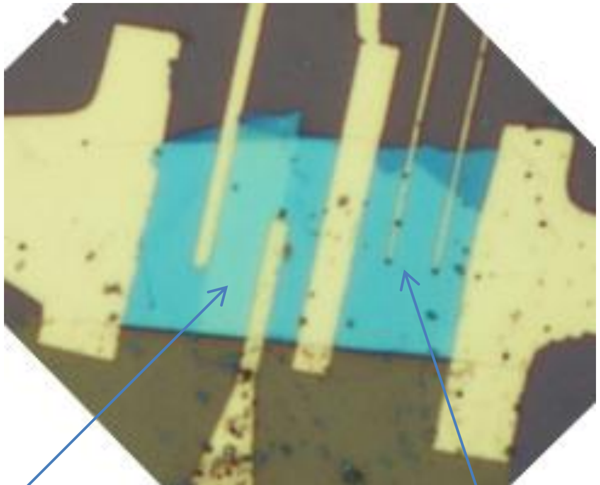


hBN encapsulated

Top surface exposed and contaminated

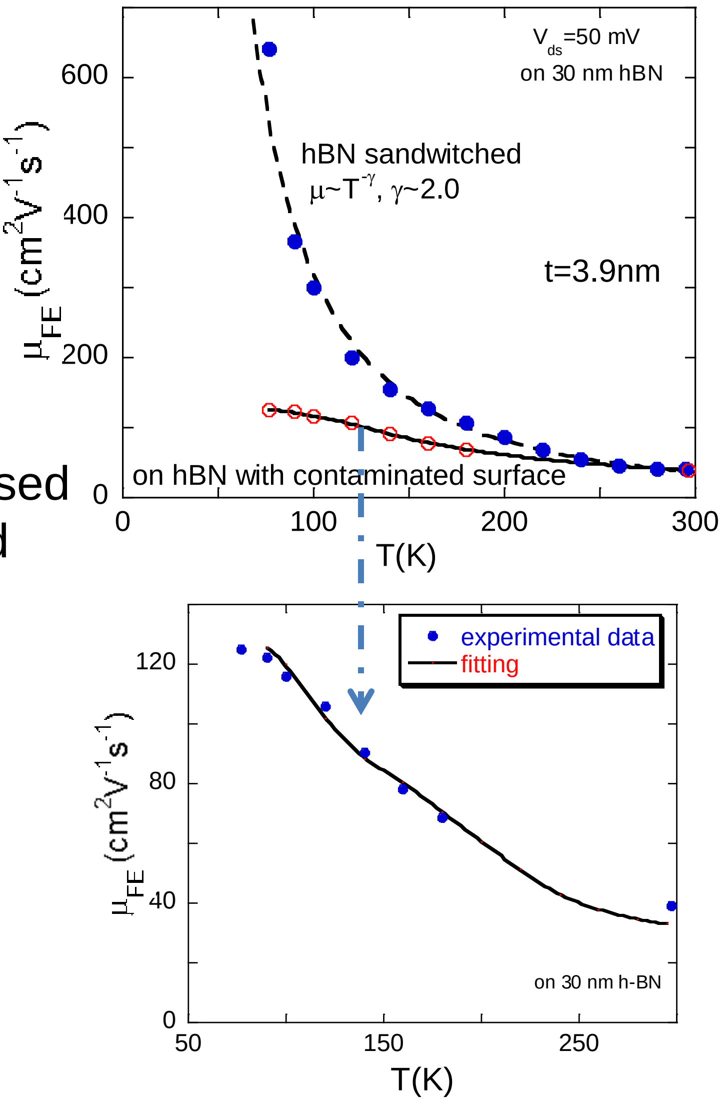


MoS_2 sandwich FET



hBN encapsulated

Top surface exposed and contaminated



Matthiessen's rule

$$\frac{1}{\mu(T)} = \frac{1}{\mu_{imp}} + \frac{1}{\mu_{ph}(T)}$$

$\boldsymbol{\mu_{imp}}$ **~ 200 cm^{2}V^{-1}s^{-1}**

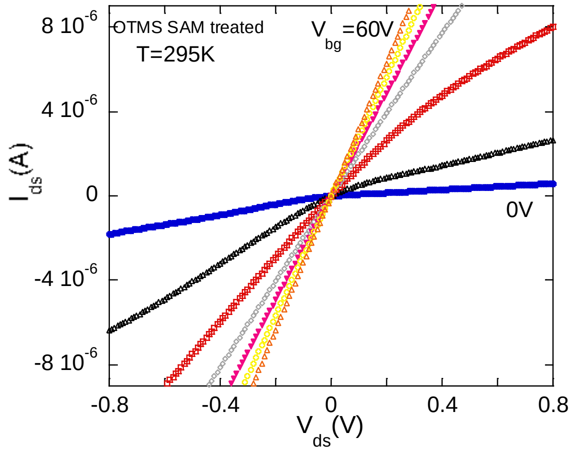
Long range charged impurity scattering limits the mobility in MoS_2 at low temperatures

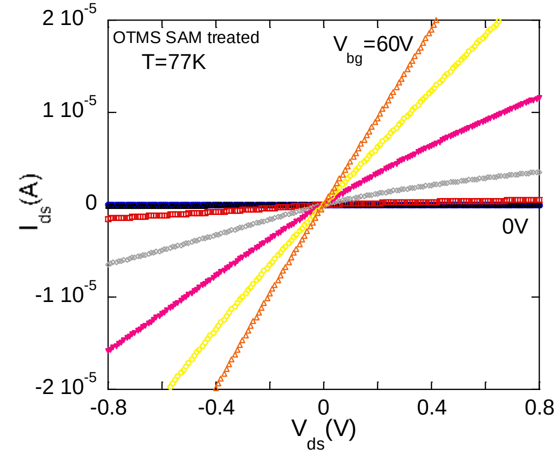
summary

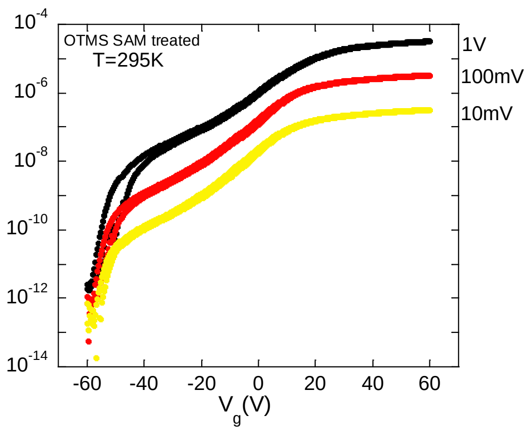
- ❖ **Fabricated MoS_2 FETs on different substrates and measured 4-probe electrical properties.**
- ❖**The observed low temperature mobility difference on different substrates primarily due to charged impurities in the substrate and surface adsorbates.**
- ❖**Room temperature mobility is nearly substrate independent indicating that it is not limited by substrate and interface effects such as charged impurities and surface roughness**
- ❖**Observed phonon limited mobility on clean h-BN substrate with stronger temperature dependence than on other substrates (power law exponent $\gamma = 2$)**

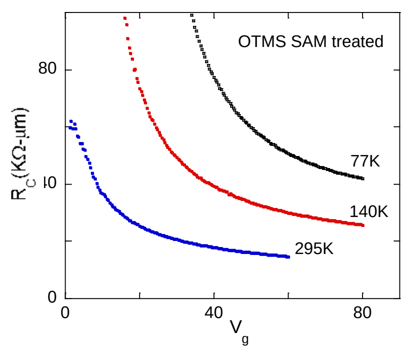
Thank you

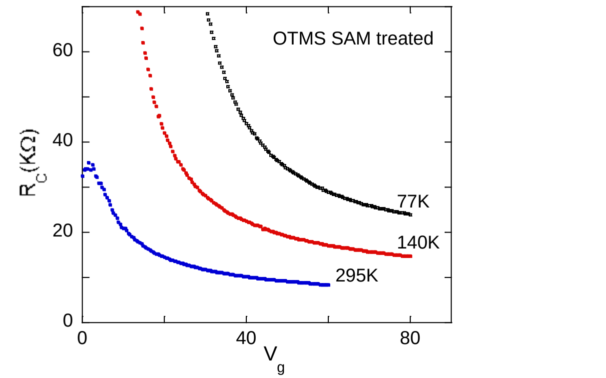
Si/SiO2 substrates were modified with OTMS SAM to remove the water
adsorbed on surface and render a charge neutral surface (hydrophobicity).

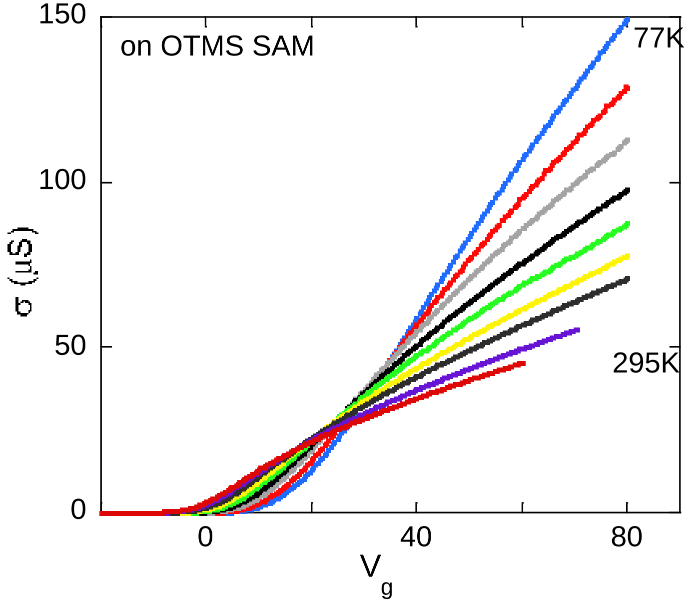




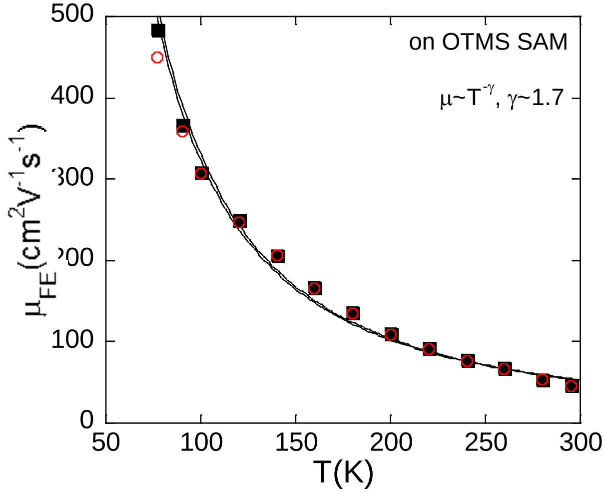




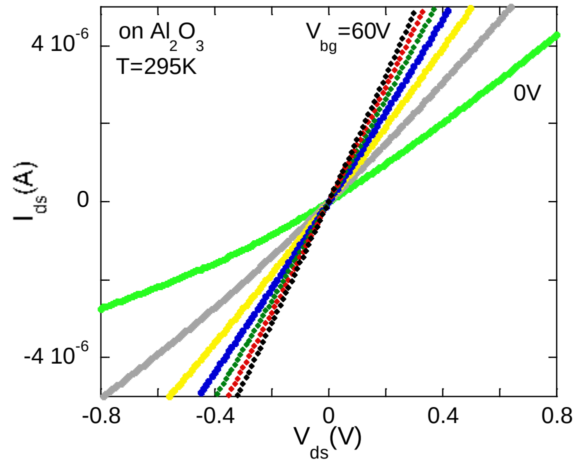


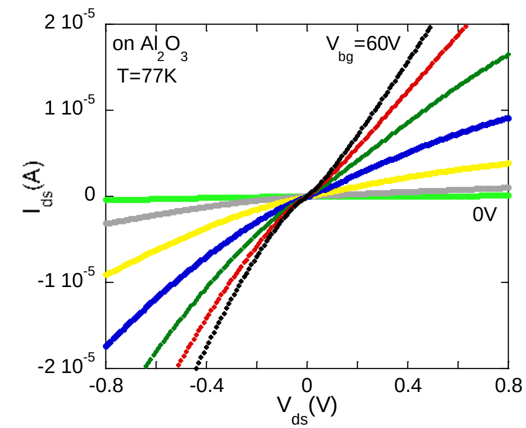


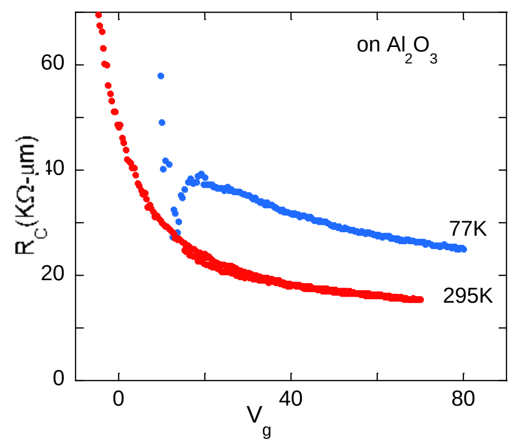
on OTMS SAM
77K
295K
150
100
50
0
0
40
80
V_g
σ (μS)

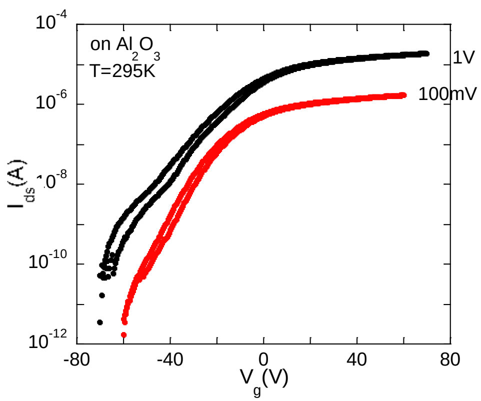


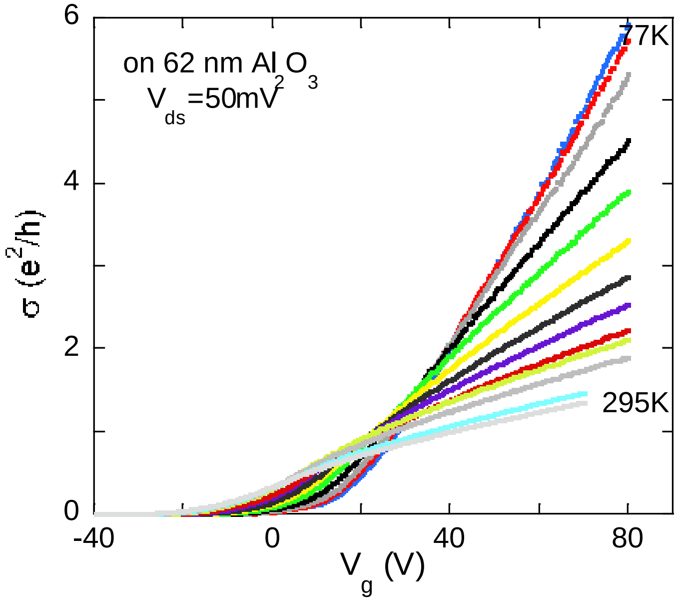
on OTMS SAM
μ~T^-γ, γ~1.7
500
400
300
200
100
0
50
100
150
200
250
300
T(K)
$\mu_{FE}(cm^2V^{-1}s^{-1})$


on Al_2O_3
T=295K
V_{bg}=60V
0V
I_{ds}(A)
V_{ds}(V)

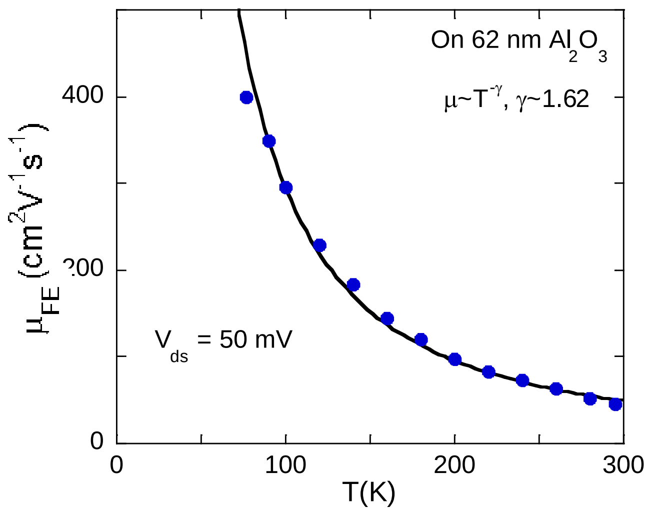

on Al_2O_3
T=77K
V_{bg}=60V
0V
I_{ds}(A)
V_{ds}(V)


on Al_2O_3
77K
295K
R_C(KΩ-μm)
V_g

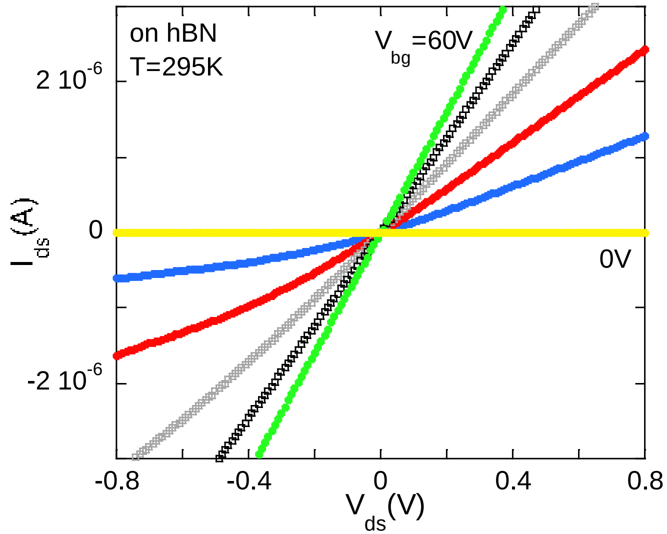

on Al_2O_3
T=295K
1V
100mV
I_{ds}(A)
V_g(V)

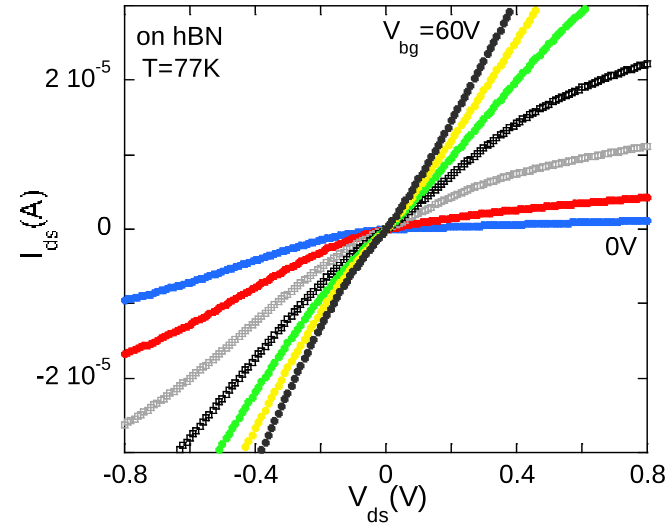


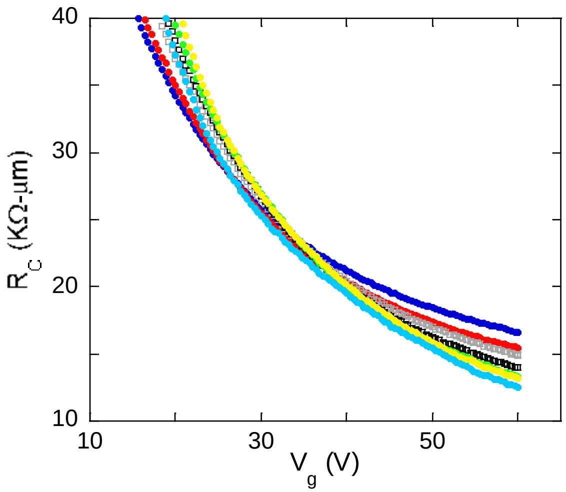
on 62 nm Al2O3
Vds=50mV
77K
295K
σ (e2/h)
Vg (V)

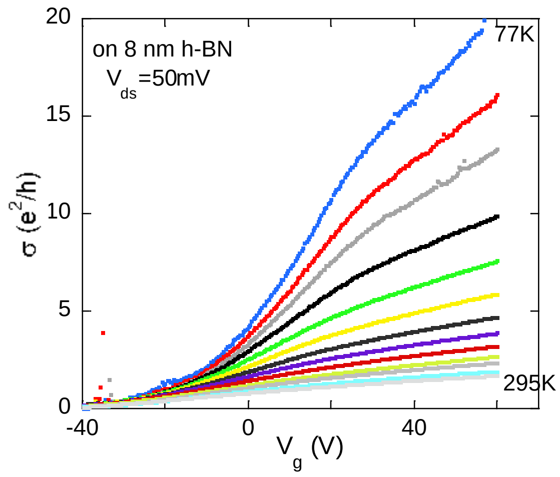


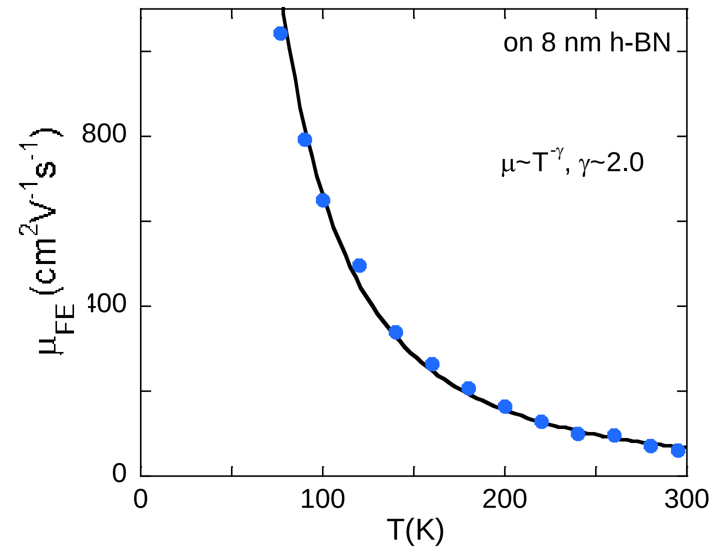
On 62 nm Al2O3
μ~T-γ, γ~1.62
Vds = 50 mV
μFE (cm2V-1s-1)
T(K)

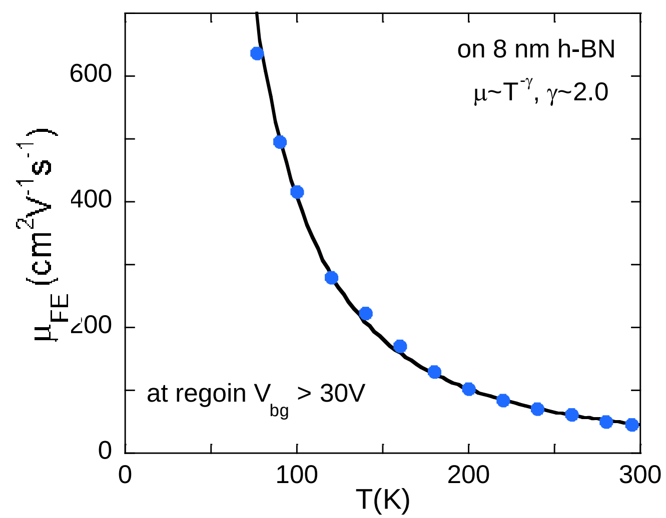

on hBN
T=295K
V bg =60V
0V
2 10-6
0
-2 10-6
I ds (A)
-0.8
-0.4
0
0.4
0.8
V ds (V)

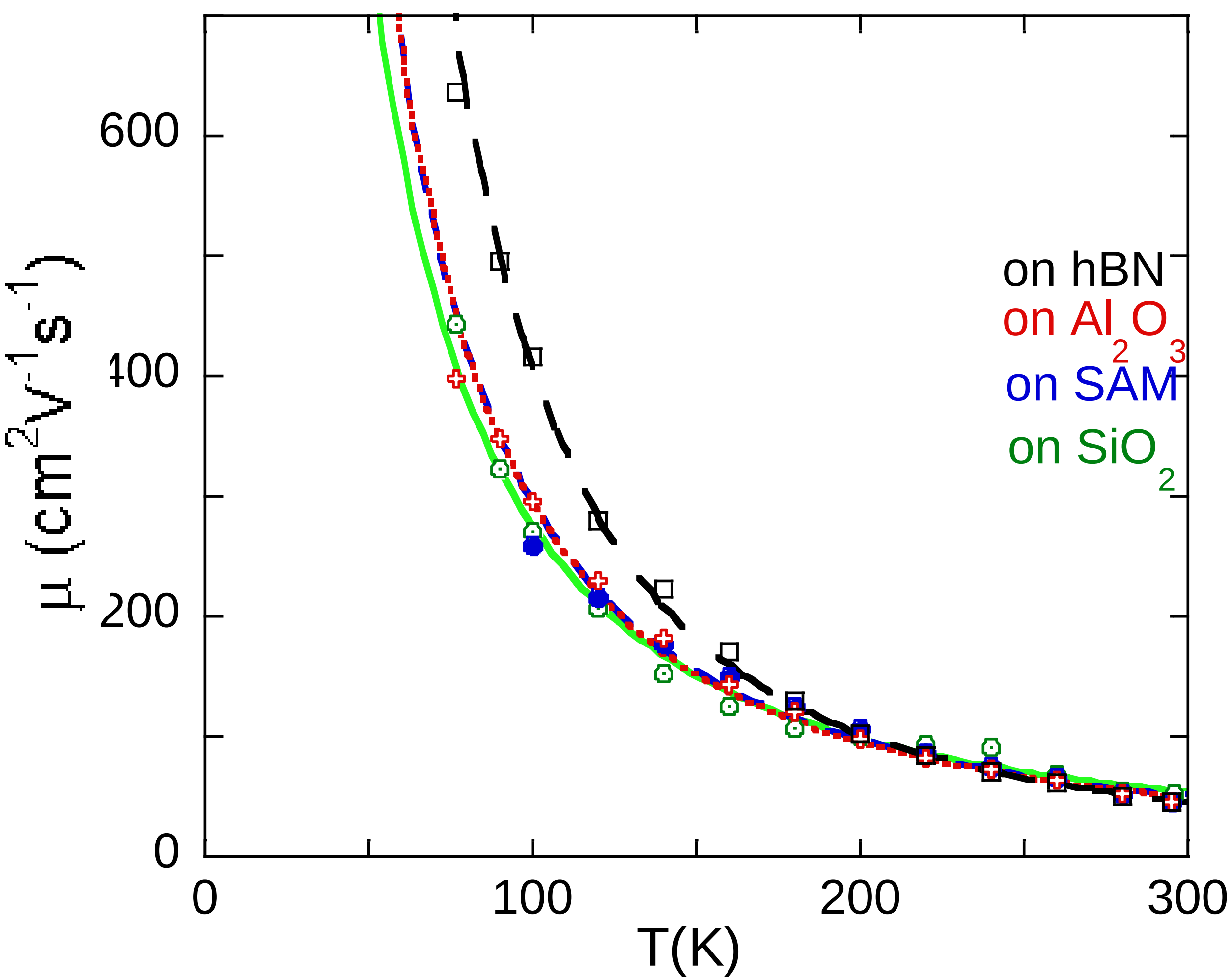

on hBN
T=77K
V bg =60V
0V
2 10-5
0
-2 10-5
I ds (A)
-0.8
-0.4
0
0.4
0.8
V ds (V)


40
30
20
10
R C (KΩ-μm)
10
30
50
V g (V)

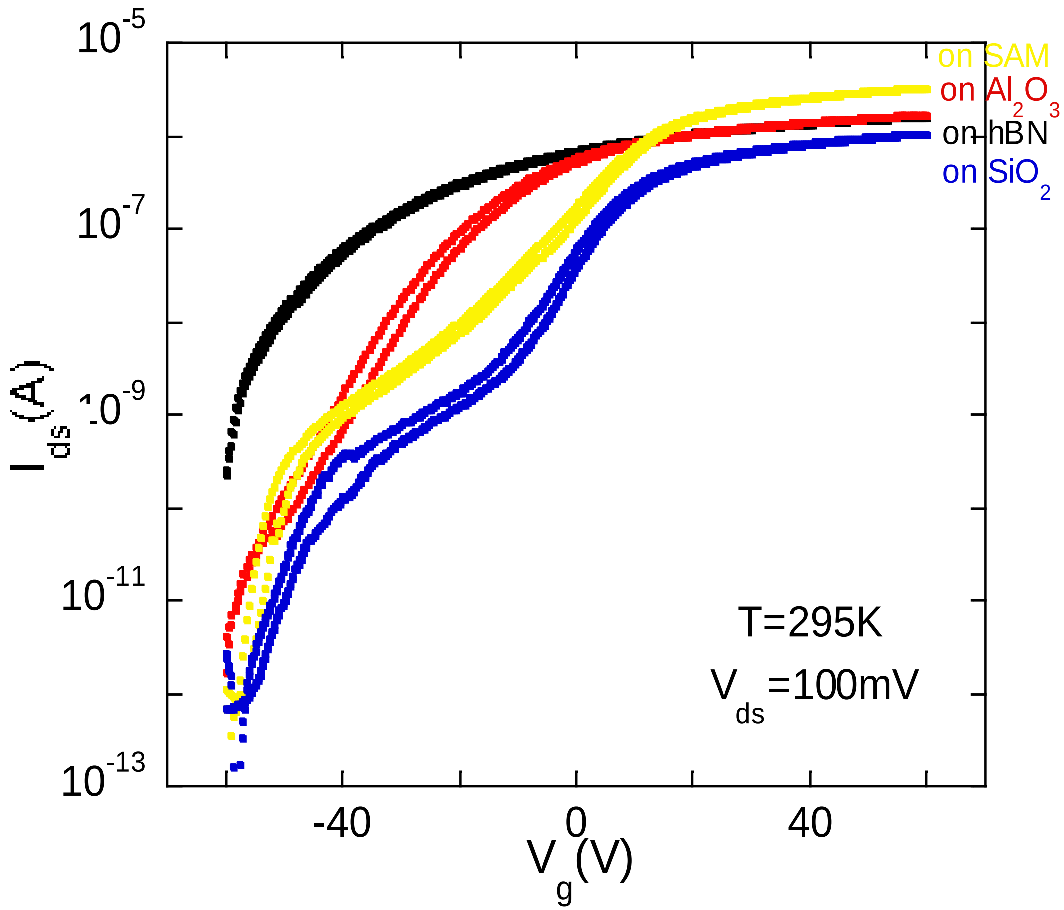

on 8 nm h-BN
Vds =50mV
77K
295K
σ (e2/h)
Vg (V)
20
15
10
5
0
-40
0
40


on 8 nm h-BN
μ~T-γ, γ~2.0
μFE (cm2V-1s-1)
T(K)
800
400
0
0
100
200
300

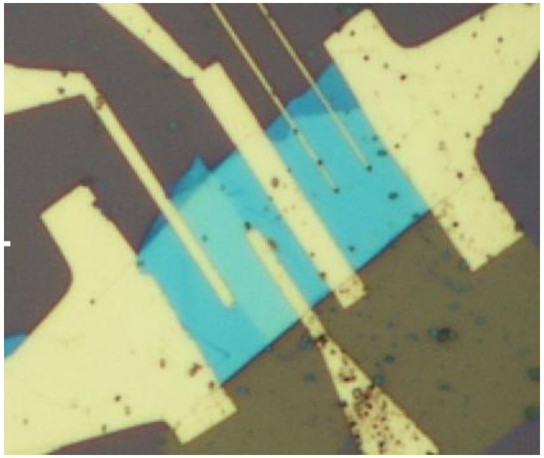

on 8 nm h-BN
μ~T-γ, γ~2.0
at regoin Vbg > 30V
μFE (cm2V-1s-1)
T(K)
600
400
200
0
0
100
200
300

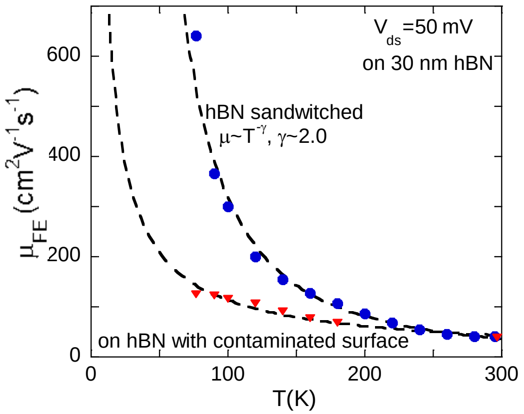


600
400
200
0
0
100
200
300
T(K)
μ (cm^{2}V^{-1}s^{-1})
on hBN
on Al$_2$O$_3$
on SAM
on SiO$_2$

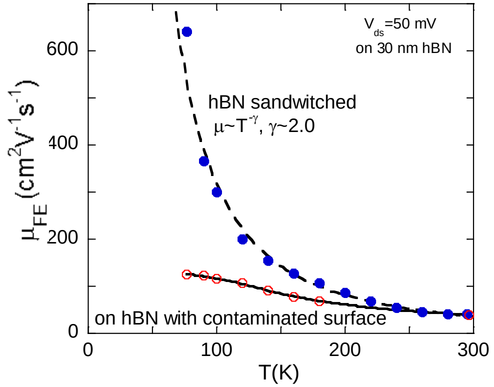


on SAM
on Al2O3
on hBN
on SiO2
T=295K
Vds=100mV
Ids(A)
Vg(V)
10-5
10-7
10-9
10-11
10-13
-40
0
40

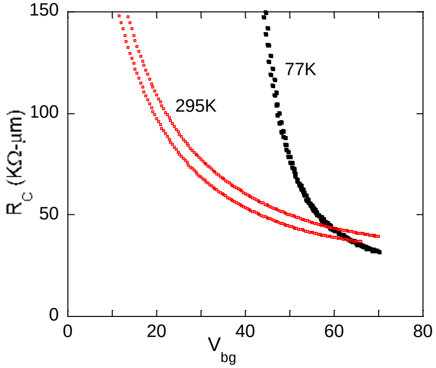




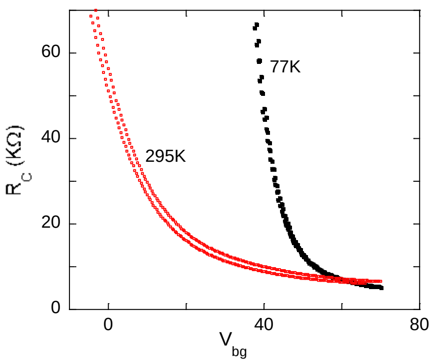
V_{ds}=50 mV
on 30 nm hBN
hBN sandwitched
$\mu \sim T^{-\gamma}$, $\gamma \sim 2.0$
on hBN with contaminated surface
μ_{FE} ($cm^2V^{-1}s^{-1}$)
T(K)



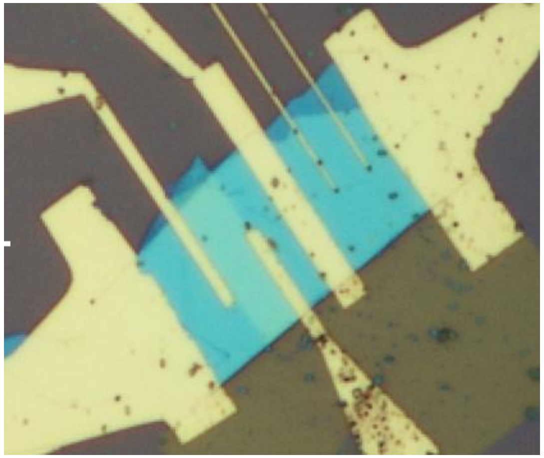
V_{ds}=50 mV
on 30 nm hBN
hBN sandwitched
$\mu \sim T^{-\gamma}$, $\gamma \sim 2.0$
on hBN with contaminated surface
μ_{FE} ($cm^2V^{-1}s^{-1}$)
T(K)

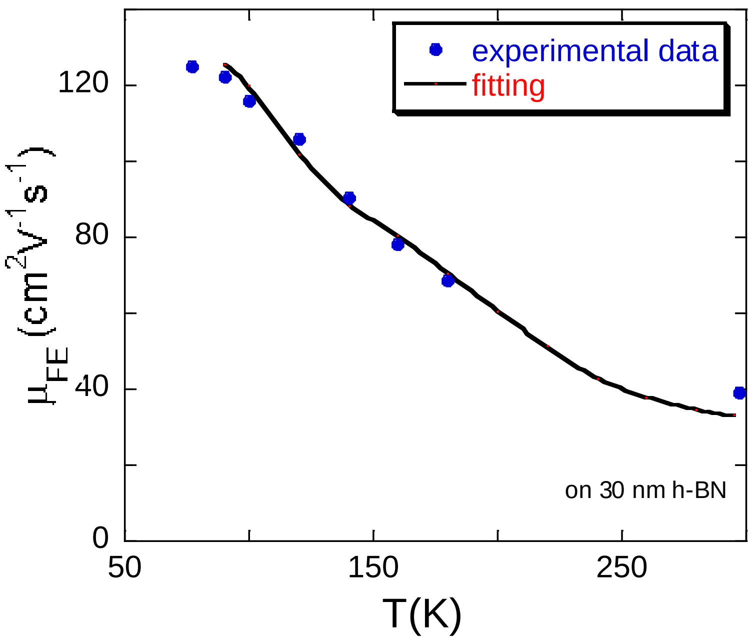


77K
295K
R_C (KΩ-μm)
V_{bg}



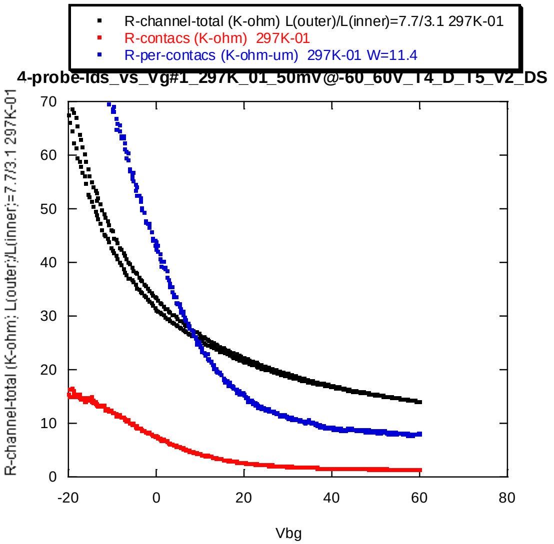
77K
295K
R_C (KΩ)
V_{bg}

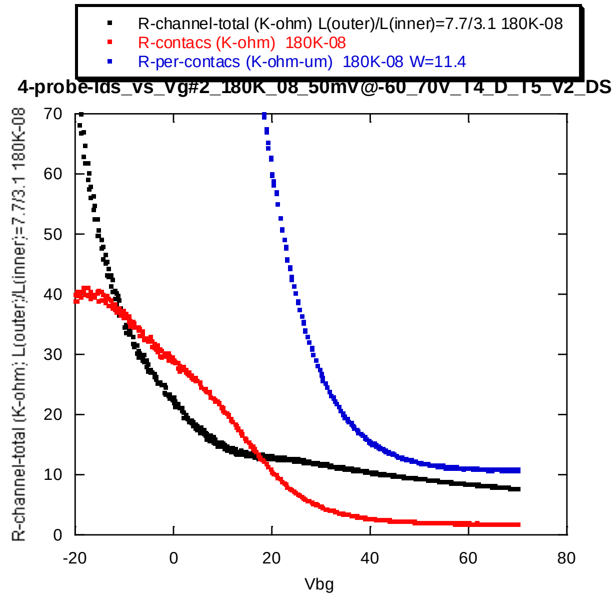


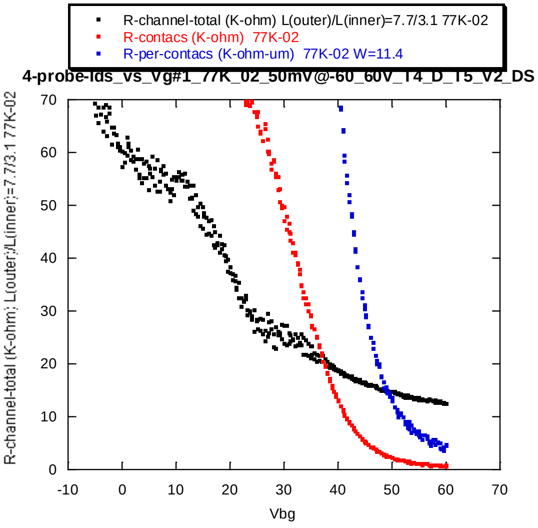


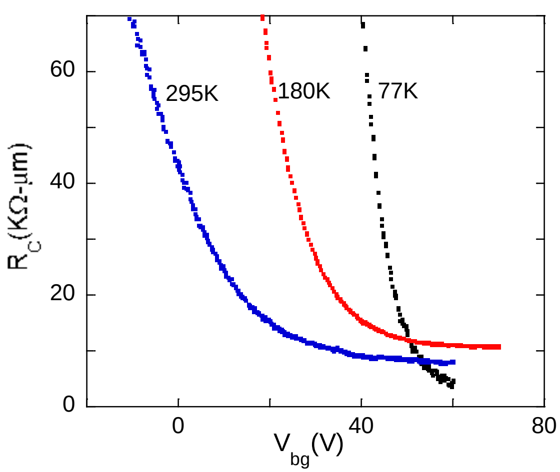
experimental data
fitting
on 30 nm h-BN
μFE (cm2V-1s-1)
T(K)
0
40
80
120
50
150
250

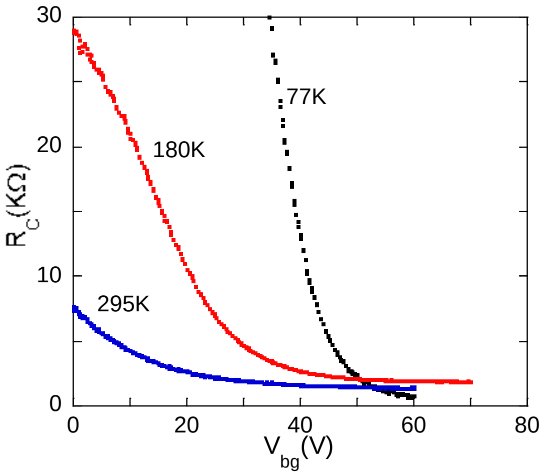
MoS2 on hBN 10-14-2014 no2 45_52   right device



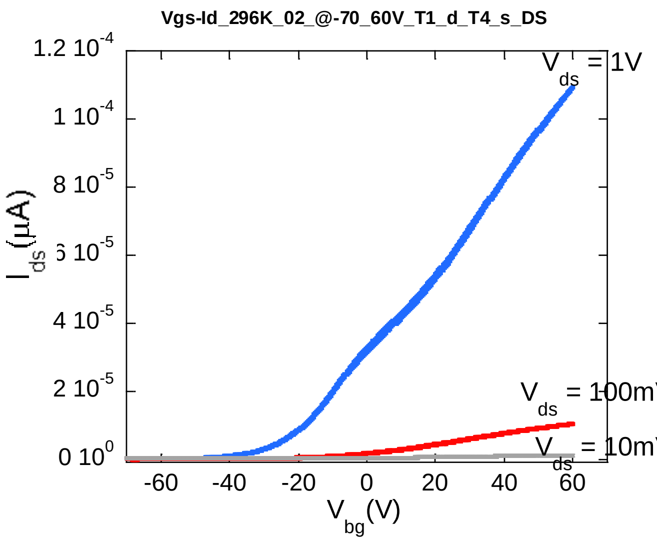


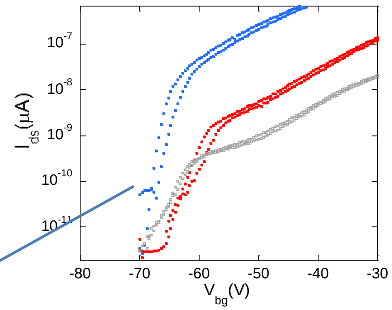


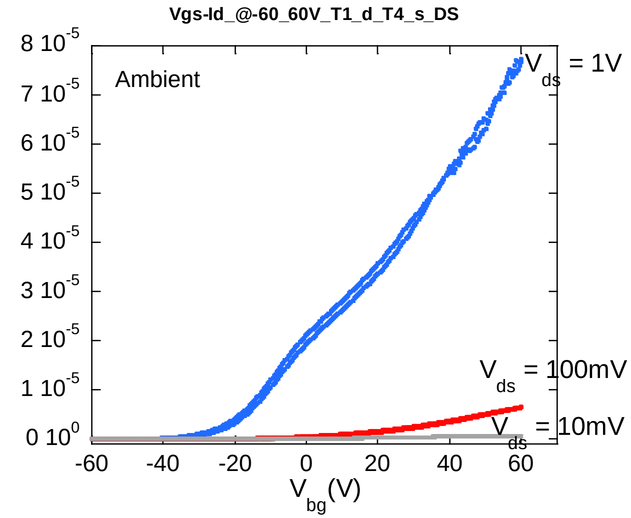


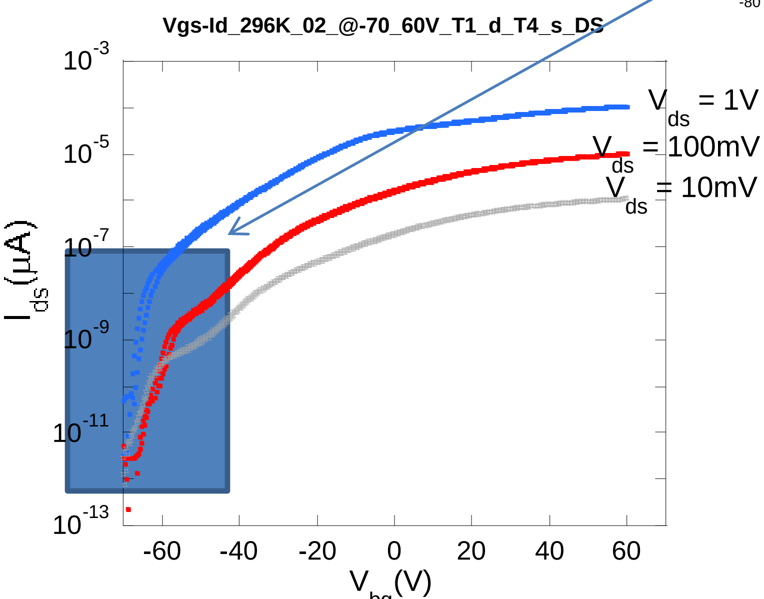


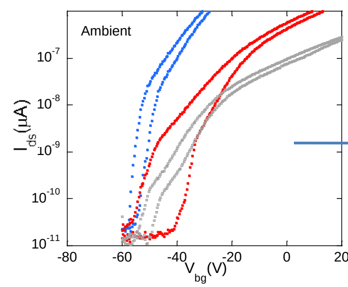
MoS_2 on hBN 08-28-2014 0-0_24

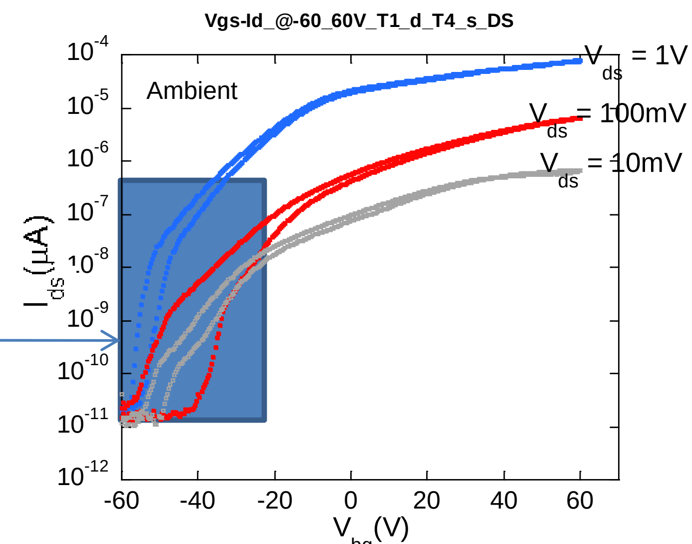












The scattering and disorder that leads to this non-metallic behavior can arise from multiple origins such as lattice defects, charged impurities in the substrate and surface adsorbates, and it has been difficult to identify their separate contributions

(Multi-terminal electrical transport measurements of molybdenum disulphide using van der Waals heterostructure device platform)

The Effect of Substrate on the Electron Transport Properties of MoS_2 Field-Effect Transistors

Substrate plays an important role in the performance of field-effect transistors (FETs) with two-dimensional transition metal dichalcogenide (TMD) channels. In this work, we systematically study the transport properties of fewlayer MoS_2 FETs consistently fabricated on various substrates including SiO_2, Al_2O_3, SiO_2 modified by octadecyltrimethoxysilane (OTMS) self-assembled monolayers (SAMs), and hexagonal boron nitride (hBN). Standard four-probe electrical transport measurement was carried out at temperatures ranging from 77 K to room temperature to understand the scattering mechanism. Surprisingly, the room temperature mobility extracted from devices on different substrates is nearly the same. In contrast, a substantially higher mobility is observed in MoS_2 devices on clean hBN substrates at low temperatures. The role of various sources of scattering originating from the substrate and the channel/substrate interface such as charged impurities, charge traps, surface roughness, and remote surface optical phonons will be discussed.

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