Oxide interface: a chance for new electronics

Lu Li
Electrons in modern technology

Charge conductance & operation

Electric field effect Transistor
Electrons in modern technology

*Spin* magnetism & information storage

Ordering of magnetic moments
Lacking a marriage between electron *spin* and *charge*

**Dream**  
*Spintronics*

**Reality**  
**Missing** of magnetic ordering in most semiconductors
Electronic materials with both properties?

1. Charge $\rightarrow$ Electric field effect
2. Spin $\rightarrow$ Magnetic ordering
Insulators \( \text{LaAlO}_3 \) and \( \text{SrTiO}_3 \)

Lanthanum Aluminate \( \text{LaAlO}_3 \) (LAO)
- band insulator gap 5.6 eV
- non-magnetic

Strontium Titanate \( \text{SrTiO}_3 \) (STO)
- band insulator gap 3.3 eV
- non-magnetic

Cubic structure

1 unit cell (u.c.)
\approx 0.38 \text{ nm}
Sharp interface between insulators \( \text{LaAlO}_3 \) and \( \text{SrTiO}_3 \)

Seminal Papers by Hwang
Nature 2002 \( \text{LaTiO}_3/\text{SrTiO}_3 \)
Nature 2004 \( \text{LaAlO}_3/\text{SrTiO}_3 \)

Mannhart & Schlom Science 2010
Conductive Interface LaAlO$_3$/SrTiO$_3$

Electronics using both *Charge* and *Spin*

Reyren et al. Science 2008
Electronic materials of both properties?

1. Charge → Electric field effect

2. Spin → Magnetic ordering
Sharp interface between band insulators

LaAlO$_3$ (LAO) film

SrTiO$_3$ (STO) substrate

Seminal Papers by Hwang
Sharp interface between band insulators

Seminal Papers by Hwang
Where is charge from?

LaAlO$_3$ (LAO) film

SrTiO$_3$ (STO) substrate

Al$^{3+}$O$_2$$^{4-}$
La$^{3+}$O$_2$$^{-}$
Al$^{3+}$O$_2$$^{4-}$
La$^{3+}$O$_2$$^{-}$
Al$^{3+}$O$_2$$^{4-}$
La$^{3+}$O$_2$$^{-}$
Ti$^{4+}$O$_2$$^{4-}$
Sr$^{2+}$O$_2$$^{2-}$
Ti$^{4+}$O$_2$$^{4-}$
Sr$^{2+}$O$_2$$^{2-}$
Ti$^{4+}$O$_2$$^{4-}$
Sr$^{2+}$O$_2$$^{2-}$

Seminal Papers by Hwang
Polar LAO film drives up electric potential

\[ \rho = -e \]

Al\(^{3+}\)O\(_2^{4-}\)  \( +e \)
La\(^{3+}\)O\(_2^{-}\)  \( -e \)
Al\(^{3+}\)O\(_2^{4-}\)  \( +e \)
La\(^{3+}\)O\(_2^{-}\)  \( -e \)
Al\(^{3+}\)O\(_2^{4-}\)  \( +e \)
La\(^{3+}\)O\(_2^{-}\)  \( -e \)
Ti\(^{4+}\)O\(_2^{4-}\)  0
Sr\(^{2+}\)O\(_2^{-}\)  0
Ti\(^{4+}\)O\(_2^{4-}\)  0
Sr\(^{2+}\)O\(_2^{-}\)  0
Ti\(^{4+}\)O\(_2^{4-}\)  0
Sr\(^{2+}\)O\(_2^{-}\)  0

La\(_{3}\)O\(_{3}\) (LAO) film
Polar

Sr\(_{2}\)TiO\(_{3}\) (STO) substrate
Non-polar

Seminal Papers by Hwang
Nature 2002  La\(_{2}\)TiO\(_{3}\)/Sr\(_{2}\)TiO\(_{3}\)
Nature 2004  La\(_{3}\)O\(_{3}\)/Sr\(_{2}\)TiO\(_{3}\)
Polar LAO film drives up electric potential

$$\rho = -e$$

LaAlO$_3$ (LAO) film
Polar

SrTiO$_3$ (STO) substrate
Non-polar
Charge transferred to reduce electric potential

Doping insulators without introducing impurities
Polar catastrophe

\[ \frac{1}{2} \text{ electron per unit cell} \]

\[ \rightarrow \text{Carrier density } \sim 3.5 \times 10^{14} /\text{cm}^2 \]
Partially filled d-band at the interface
Two-dimensional magnetic conductor?

1. Dimensionality?
2. Magnetic ground state?

Partially filled d-band at the interface
Electrons in Ti\(^{3+}\) orbitals

For d\(_{xy}\), magnetic moment \(\sim \mu_B / e\)

Magnetic moment in the ground state?

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<th>Charge</th>
<th>Al(^{3+})O(_2^{4-})</th>
<th>La(^{3+})O(_2^{2-})</th>
<th>Al(^{3+})O(_2^{4-})</th>
<th>Ti(^{4+})O(_2^{4-})</th>
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Holes on the surface, at O sites?
Electric field effect in oxide interface

Li et al. Science 2011
Capacitance Change $\leftrightarrow$ Electric field effect

Capacitance $\sim$ Area / distance

Gate voltage $V$

Interface conductive at $V > 0$
Capacitance Change ⇄ Electric field effect

Capacitance $\sim$ Area / distance

Gate voltage $V$

Interface insulating at $V < 0$
Capacitance Step ↔ Electric field effect

Li et al. Science 2011

$C (\text{nf})$

$V_g (\text{V})$

$10 \text{ u.c. LAO on STO}$

$circular \text{ top gate with } d = 350 \text{ um}$

$f = 5 \text{ Hz}$

$n \sim 2 \times 10^{12} /\text{cm}^2$
Capacitance enhancement

possible way to reduce heat dissipation in computer chips

$\text{n} \approx 2 \times 10^{12} /\text{cm}^2$

Li et al. Science 2011
Oxide interface

1. Charge \rightarrow Electric field effect

2. Spin \rightarrow Magnetic ordering
Challenge I: how to measure the magnetic moment of a single atom layer?
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Torque on moment: $\tau = m \times H$
Torque magnetometry

Torque on moment: $\tau = m \times H$

Deflection of cantilever $\rightarrow$ torque $\tau$
Torque magnetometry

Torque on moment: \( \tau = m \times H \)

Deflection of cantilever \( \rightarrow \) torque \( \tau \)
Cantilever setup of bismuth

1. Magnetic moment $\Delta m \sim 10^{-13}$ A.m² at 10 T
   (SQUID MPMS, $\Delta m \sim 10^{-9}$ A.m²)
2. Works up to 45 Tesla, at 20 m K ~ 300 K

Li, Cava, Uher, Hebard, Ong ... Science (2008)
Torque curve examples

Paramagnet

\[ M \text{ proportional to } H \]
\[ \text{torque } = M \times H \sim H^2 \]
Torque curve examples

Soft Ferromagnet

![Diagram of a soft ferromagnet with arrows indicating magnetic orientation.]

![Graph showing the relationship between magnetic moment (M) and magnetic field (H). The graph shows a step-like increase in M as H increases, followed by a linear decrease in Torque with respect to H.]

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Challenge II: how to make sure the signal really comes from the interface?
Control experiments on LaAlO$_3$/SrTiO$_3$ interface

5 u.c. LaAlO$_3$ on SrTiO$_3$

0 u.c. LaAlO$_3$ on SrTiO$_3$
Tiny background signal from the cantilever

\[ T = 300 \text{ mK}, \quad \text{angle } \phi \sim 15^\circ \]

Cantilever only
Small torque signal of sample without LaAlO$_3$
Large torque signal of sample with LaAlO$_3$
Magnetic Ordering from non-magnetic materials

\[ \mu_0 H \text{ (T)} \]

Torque \((10^{-10} \text{ N m})\)

\[ \mu_0 H \text{ (T)} \]

\[ m (10^{-10} \text{ A m}^2) \]

5 u.c. LAO/STO

T = 300 mK
Comparison of torque of the LAO/STO interface and LAO film on LAO substrate

![Graph showing torque comparison]

- **Sample 1**
  - 5 u.c. LAO/STO
  - $T = 300 \text{ mK}$

- **Bare LAO substrate**
  - $T = 1.5 \text{ K}$

- **5 u.c. LAO film on LAO substrate**
  - $T = 1.5 \text{ K}$

**NOT** from the disorder of the LAO film
Magnetization signal
NO big change up to 40 K
Coexistence of superconducting state and magnetic ordering

Superconducting $T_c \sim 120$ mK
Superconductivity without time-reversal-symmetry

- Triplet Pairing?
- Half vortex?
- Majorana Fermion in 2D?
- Topological Quantum Computation?

LaAlO$_3$/SrTiO$_3$

He$^3$ superfluid A phase
p-wave Sr$_2$RuO$_4$
Summary

Two-dimensional magnetic system at LaAlO$_3$/SrTiO$_3$

- Electric field effect and capacitance enhancement
- Detection of in-plane magnetic moment of single atom layer interface