Why looking at oxide structures?

1947 the transistor

J. Bardeen, W. Brattain, W. Shockley

Photo: Bell Labs

Very impressive progress

Transistor history:

- 1947 discovery: 1 transistor
- 1971 Intel 4004: 2,300 transistors
- 1993 Intel Pentium: 3.1 million transistors
- 2001 Intel Pentium 4: 42 million transistors
- 2007 Intel Dual-Core Titanium 2: 1.7 billion transistors

2014: ~ $2.5 \times 10^{20}$ transistors fabricated
Silicon - a magic material?

A simple electron system described by single particle physics

Adapted from J. Mannhart

You need to add an interface: Si/SiO₂

QUASI-ELECTRIC FIELDS AND BAND OFFSETS: TEACHING ELECTRONS NEW TRICKS

Nobel Lecture, December 8, 2000
by
HERBERT KROEMER
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1. INTRODUCTION

Heterostructures, as I use the word here, may be defined as heterogeneous semiconductor structures built from two or more different semiconductors, in such a way that the transition region or interface between the different materials plays an essential role in any device action. Often, it may be said that the interface is the device.

One of the issues: dissipation

A computer farm in Sweden

Searching for / studying other materials


Graphene

(a) MoS₂ monolayer

Dichalcogenides

Univ. Twente
**Transition metal oxides - perovskites**

$\text{ABO}_3$

**Perovskite - CaTiO$_3$**

Perovskite structure - a very common structure on Earth

Oxides → Oxide structures → Oxide interfaces

**Oxides display a variety electronic properties**

Perovskite Structure


**Complex phase diagrams**

**Manganites**


**Cuprates**


**Like Lego bricks**

PbTiO$_3$ ferroelectric $T<T_C$

Tetragonal and ferroelectric

$a=b=3.99\text{Å}$, $c=4.12\text{Å}$

SrTiO$_3$ paraelectric at all temperatures

$a=b=c=3.905\text{Å}$
The LaAlO$_3$/SrTiO$_3$ interface

LaAlO$_3$: band insulator
Δ = 5.5 eV, κ = 24

SrTiO$_3$: band insulator
Δ = 9.0 eV, κ = 1500 K

quantum paraelectric

A conducting interface

A high-mobility electron gas at the LaAlO$_3$/SrTiO$_3$ heterointerface


μ ~ 1000 cm$^2$/Vs
Magnetism

Brinkman et al.

A. Brinkman et al., Nat. Mater. 6, 493-496 (2007)
Aranda et al., Nat. Commun. 2, 188 (2011)
J. A. Brinkman et al., Nature Physics 7, 186 (2011)
J. A. Bert et al., Nature Physics 7, 287 (2011)

A new field of research

Breakthrough of the Year
21 DECEMBER 2007 VOL 318 SCIENCE www.sciencemag.org
Published by AAAS

5 BEYOND SILICON! Ten years ago, semiconductors were a scientific curiosity. Then researchers tried putting one type of semiconductor on another, and suddenly we had diodes, transistors, microprocessors, and the whole electronics age. Starting results this year hint at a similar kind of discovery at the interface of a different class of materials: transition metal oxides. Transition metal oxides first made headlines in 1959 with the Nobel Prize-winning discovery of high-temperature superconductors. Since then, solid-state physicists keep finding unexpected properties in these materials—including colossal magneto-resistance, in which small changes in applied magnetic fields cause huge changes in electrical resistance. But that should only start what one oxide rubs shoulders with another.

If different oxide crystals are grown in layers with sharp interfaces, the effect of one crystal structure on another can shift the positions of atoms at the interface, alter the population of electrons, and even change how

Transistors conduct. It is a promising research direction for how to build transistors that work better. These would be a real boost to the electronics age. 

Superconductivity at low T

Superconducting Interfaces Between Insulating Oxides
Science 317, 1198 (2007)
Outline

Origin of the conductivity
FE control of the electronic properties
Electronic structure
Superconductivity
Exciting developments

The «Geneva» LaAlO$_3$/SrTiO$_3$ Team

Stefano Gariglio
Margherita Boselli
Adrien Waelchli
Gernot Scheerer

Andrea Caviglia (now in Delft)
Nicolas Bayens (Censi's group)
Claudia Cancio-Forti (DUP)
Daniele Serroni (Naples)
Wei Liu (KLA-Tencor)
Alexandre Fête (Rolex)
Zhengeng Wu (EMPA)
Denver Li (Stanford)
Alexey Kuzmenko
Dirk van der Marel

and collaboration with
Marc Gabay (Orsay)
Philippe Ghosez (Liège)
Jochen Mannhart (MPI Stuttgart)

Why is the Interface Conducting?
The polar catastrophe scenario

\[ \text{SrO}_0 \text{LaO}^+ \text{AlO}_2^- \]

\[ \text{TiO}_2 \]

\[ \text{LaAlO}_3 \]

\[ \text{SrTiO}_3 \]

Testing the polar catastrophe scenario

\[ E = (\sigma_0 / \varepsilon_r \varepsilon_0) \Rightarrow d_c = V_d / E \]

with \( V_c = 3.35 \text{ V} \), \( \sigma_0 = 3 \times 10^{14} \text{ e/cm}^2 \) and \( \varepsilon_r = 25 \), \( d_c = 3.5 \text{ u.c.} \)

See also R. Pentcheva and W. Pickett PRL 102, 107602 (2007)

LaAlO\textsubscript{3} critical thickness

\[ S. \text{ Thiel et al. Science 313, 1942 (2006)} \]

\[ N. \text{ Nakagawa et al., Nature Materials (2006).} \]
Oxygen vacancy formation at the LAO surface


See also,
Liping Yu and Alex Zunger Nat. Com. 2015
J. Zhou et al. Singapore, UBC

Doping Control - Electric Field Effect

Doping control using the field effect

~2-8×10^{13}/cm^2
mobilities 100-1000 cm^2/Vs

A lot of work here in France

SrO
TiO\textsubscript{2}
LaO
AlO\textsubscript{2}
(001)

TiO\textsubscript{2}-plane

3.9 Å
**Transport and field effect control**

Side gating

**Modulation of SC**


**A superconducting switch**

With increasing (negative) $V_g$


**System phase diagram**

$T_c \propto (V - V_c)^{2/3}$

See also C. Bell et al. PRL 103, 226802 (2009).
**Other conducting oxide interfaces**

Two-dimensional superconductivity at a Mott insulator/band insulator interface LaTiO$_3$/SrTiO$_3$

N. Bergeal
J. Lesueur
ESPCI

**Confinement and electronic structure**

RT d<7nm
12 nm at low T


At the interface, the electrons are on the SrTiO$_3$ side, in the Ti 3d band

**Quantum Confinement**

8K (b)

At the interface, the electrons are on the SrTiO$_3$ side, in the Ti 3d band

dxz  dyz  dxy  dx$^2$ - y$^2$  dz$^2$

t$_{2g}$
e$_g$
t\textsubscript{2g}-e\textsubscript{g} splitting and crystal field

Electrons are in t\textsubscript{2g} orbitals

Confinement and electronic structure

Multi-bands behavior
Bulk and Interface Superconductivity

Superconductivity in bulk SrTiO$_3$

See also X. Lin et al. PRL 112, 207002 (2014)

Bulk and interface SC

Bulk and interface SC

D. Valentinis et al. PRB 96, 094518 (2017)

Bulk data from X. Lin et al. PRL 112, 207002 (2014)
Some open questions:
Superconductivity in SrTiO$_3$
The Possible Role of Spin-orbit
The Underdoped Regime

Origin of the SC state

A possible mechanism for superconductivity in doped SrTiO$_3$
D. van der Mael, F. Baratella, C. W. Rischau$^1$
$^1$Department of Quantum Matter Physics, University of Geneva,
24 Quai Ernest-Ansermet, 1211 Geneva 4, Switzerland

Preprint
Paired through the exchange
of two TO phonons

Proximity to a QCP, ferroelectric fluctuations

Superconductivity in the vicinity of a ferroelectric quantum phase transition
S. E. Rowley$^{12}$, C. Enderlein$^{3}$, J. Feioz de Oliveira$^1$, D. A. Tompsett$^2$, E.
Hugues Sautier$^3$, E.S. Santos$^1$ and G. G. Lonzarich$^3$

Preprint
$T_c$ decreases with P and the increase of the frequency of the soft
TO polar phonon mode - pairing through hybrid longitudinal modes

SrTiO$_3$ - a quantum paraelectric

K.A. Müller and H. Burkard PRB 19, 3593 (1979)

M. Gabay and J.-M. Triscone
N & V Nature Physics 2017

O$^{18}$-O$^{16}$

A. Stucky et al. Scientific reports 6, 37582 (2016) - O$^{16}$ doped SrTiO$_3$


La-doped SrTiO$_3$ - O$_{16}$O$^{18}$
$T_c$ around 0.5K
Spin-orbit Coupling

\[ \alpha = \frac{\hbar}{m} \sqrt{\frac{\hbar c H_{so}}{2}} \]

\[ \Delta = 2\alpha k_F \]

Very large tunable spin-orbit coupling

\[ \Delta = 10\text{meV} \] is much larger than the SC gap (\(\sim 40\mu\text{eV}\))

Rashba spin-orbit coupling

\[ H_R = \alpha (\vec{k} \wedge \vec{n}) \cdot \vec{\sigma} \]

The electrons experience an internal magnetic field oriented in the 2DEL plane

Exciting Developments

Role of spin-orbit coupling on superconductivity?
The samples A, C and D were measured in a dilution refrigerator. The sample B was measured in a cryostat. All samples were measured using a standard Hall bar configuration. The thickness of the LaAlO$_3$ substrates was determined by pulsed laser deposition, at 650°C for 1 h to remove any native oxide layer. The electrical contacts to the LAO$_3$/STO/STO interfaces were made by ultrasonic bonding with Al wires. The humidity of the environment was 35%. The sample D was capped with a 140 nm thin metal-coated Al film.

Resolution is determined by the tip (≈ 20 nm). In the inset of each panel the Hall conductance, $g_{xy}$, is shown in units of $e^2/h$. The indices label the integer multiples of the quantum conductance unit, $\epsilon R_e$. The corresponding values from the analysis of $dR/dH$ are shown in the parentheses. Note that the tabulated values assume no degeneracy factor. The plateau-like features in $R_{xy}(H)$ for the four samples, measured at 5.1 T, 4.7 T, 4.5 T and 3.8 T, are shown in the parenthesis. In the inset of each panel we plot the Hall conductance, $g_{xy}$, for each sample, and examine the corresponding values of the amplitude of oscillations, $g_{fi}$. In the inset of each panel we show the images of the 2DES using Cryo-SNOM. The resolution is determined by the tip (≈ 20 nm). The superimposed plateau-like structure (the slight non-linearity at $H$ close to 4 T) is more than 50% of the total resistance, indicating the high quality of the samples.

The indices marking the plateaus become more apparent with increasing $H$. In the inset of each panel we show the images of the 2DES using Cryo-SNOM. The resolution is determined by the tip (≈ 20 nm). The superimposed plateau-like structure (the slight non-linearity at $H$ close to 4 T) is more than 50% of the total resistance, indicating the high quality of the samples.
Writing nanoscale electronic circuits

Fig. 2. SketchFET device. (A) Schematic diagram of SketchFET structure. S, source electrode; D, drain electrode; G, gate electrode. (B) I/V characteristic between source and drain for different gate biases $V_{G0} = -4 \, V$, $-2 \, V$, 0 V, 2 V, and 4 V. (C) Intensity plot of $I_D (V_{SD}, V_{GD})$.

Imaging AFM written nanowire

Inverse Rashba-Edelstein effect

$J_{dc} = 2\pi j_0\alpha x/\hbar$
A spin-polarized 2DEL

Naples group

Tunable spin polarization and superconductivity in engineered oxide interfaces

Kondo n\text{c} FM (below n\text{c}, no xz, yz)

EuTiO\text{3} - ferro below 7-8K


A new oxide electronics?

2009-2014 - a million transistors

R. Jany et al.
J. Mannhart - MPI Stuttgart

Beyond silicon?

1947 Bell Labs

2009 UNIGE

Reviews


Stefano Gariglio, Marc Gabay and Jean-Marc Triscone
APL Materials 4, 060701 (2016)