MoS₂ film thinning on high-temperature sputtering for enhancement-mode nMOSFETs

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More Moore, More than Moore
Moore’s Law since 1965

“The number of transistors on integrated circuits doubles approximately every two years.”

Gordon E. Moore, 1965

![Image of Gordon Moore]

![Graph showing the number of transistors increasing over time]

- Pentium 4: 2000 - 42 Million Tr.
- Core i7: 2011 - 2.3 Billion Tr.
- Intel, 2012 - 42 Million Tr.
- Intel, 2014 - 2.3 Billion Tr.

Moore’s law slope
Limitations of conventional silicon

**Mobility**
Performance indicator of how fast electrons can move
 e.g., related to the clock speed of PC

![Diagram showing n and p types of semiconductor with arrows indicating electron movement.](image)

**Future**
**Up to now**


**Thin and high mobility** are needed at the same time
Our solution
- 2D material with sputtering -
2D material for future transistors

**MoS$_2$** Molybdenum disulfide (semiconductor) utilized as solid lubricant so far

- Abundant
- Flexible
- Transparent
- High heat resistivity

Promising material for ultra-thin transistor

![Graph showing mobility vs thickness of channel for MoS$_2$ and Silicon with data points for B. Radisavljevic et al. (2011), K. Uchida et al. (2002), S. Das et al. (2012), and H. Wang et al. (2012).]
MoS$_2$ formation process

Conventional

- Exfoliation (taking off MoS$_2$ film from the crystal)
  - Unsuitable for mass production
  - Difficult to control amount of impurities

Our proposal

- Sputtering method
  - Suitable for mass production
  - Easy to control amount of impurities
Current achievements
Thickness dependent growth of MoS$_2$

Different growth direction at 10nm

< 10nm, lateral layer,

Suitable for *scaled* CMOS
Carrier density of sput. deposited MoS$_2$

- **B. Radisavljevic, et al, (2013).** (exfoliation)
- **Decrease in carrier density (~ $10^{-3}$ times)**

**This study** (high temp. sputtering)

<table>
<thead>
<tr>
<th>Lateral layers</th>
<th>Perpendicular layers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Density</td>
<td>$1.1 \times 10^{17}$ cm$^{-3}$</td>
</tr>
</tbody>
</table>

Lateral layer region exhibits low carrier concentration $N_d$ of $10^{17}$ cm$^{-3}$ with lateral growth
Future direction & Conclusion
Threshold voltage expectation with high-temp. sput. deposited MoS₂

Normally-off can be achieved with $N_d = 10^{17}$ cm$^{-3}$, under $Q_f$ improvement below $10^{11}$ cm$^{-2}$
Future society using MoS$_2$ transistors

- Paper-like display
- Transparent smartphone

Supercomputer into one laptop?
Conclusion

• Better crystallinity MoS$_2$ film lateral to substrate can be obtained with high-temperature sputtering.

• Carrier concentration of laterally grown MoS$_2$ exhibit a low carrier density of $10^{17}$ cm$^{-3}$.

• With this carrier concentration, normally-off characteristics can be achieved, if $Q_f$ at the gate dielectrics is less than $10^{11}$ cm$^{-2}$.
Resistance depending on thickness

Four-probe method

Sputtering at 300 °C

High resistance at the surface owing to crystallinity difference

High Resistivity

Low Resistivity

SiO$_2$

High resistance at the surface owing to crystallinity difference
MoS$_2$ film on various substrate

**Sputtering method** often utilized in silicon process

Argon gas $\sim$ 1 Pa

Accelerated argon ions

MoS$_2$ Target

Substrate

RF

Appropriate for mass production

Decrease in carrier density (~ $10^{-3}$ times)

This study (high temp. sputtering)
Orientation differences

- SiO₂
- MoS₂
- Perpendicular to substrate

Thickness (nm)

RMS Roughness (nm)

AFM (1.0 × 1.0 mm)

Lateral layers

Perpendicular layers
Succeeded forming MoS$_2$ layers

Five layers of MoS$_2$ are obtained → Ultra-thin transistor will be realized
Billions of transistors for prosperous society

Integrated Circuits (IC chip)

IT Products

Social Systems
Graphene – 2D material made from a pencil

Pencil (carbon) → Graphite → Graphene

Excellent mobility

= 40000 (Silicon: 1400)

Nobel Prize in Physics 2010

Metal-like behavior, not semiconductor
Transistors — greatest invention of 20th century

Nobel Prize in 1956  Shockley, Bardeen and Brattain

First transistor, invented in 1947 as novel substitute for vacuum tube

~1947

Vacuum tube

Transistor (= one vacuum tube)

Integrated Circuit (= billions of Tr.)
Transistors — made of semiconductors

Semiconductor

Small

Electrical resistance

Large

Conductor

Metal

Semiconductor

Silicon

Add very few impurities

Insulator

Rubber

n-type semiconductor

Free electrons: abundant

p-type semiconductor

Free electrons: lacking
Why are transistors needed?

Binary digits: 1 & 0 are available

Transistor

Switch off

Switch on

Voltage off

Voltage on

Metal

Insulator

Electron

n

p
Why are transistors needed?

Switch

Binary digits: 1 & 0 are available

Transistor

IC chip

All IT products and networking system are using transistors
If there is no transistors in the world...
More integration makes more prosperous society