New materials on horizon for advanced logic technology in mobile era

Kelin J. Kuhn, TED 2012

Basic components of the ultimate CMOS device.

Franz Kreupl, IFX 2003
Outline

- Introduction
- Comparing carbon nanotubes with our wish list for the "switch of the future"
- Bridging the gap: Show a strategy how to bring nanotubes into the semiconductor eco-system
- Conclusions
Limited time window for alternatives

- III-V process is not ready
- III-V becomes worse than Si

SiGe, Ge, GeSn

Opportunity

Technology node, nm

32 22 16 11 8 6 4

V. Moroz, Synopsis, 2011

- Si-based CMOS is still the mainstream for downsizing to sub-10 nm.
Electrostatics favors gate-all-around

- Lowest short-channel effects with Gate-All-Around

Kelin J. Kuhn, IEDM 2012

Franz Kreupl, IFX 2003
Carbon nanotubes do gate-all-around

- Very high on-current
- No/low DIBL

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work: Franklin et al., IEDM 2012
patent: Kreupl & Seidel US 7646045
Contact resistance: major headache

At 10 nm half-pitch one contact will be > 30 kOhm

would like purely metallic contacts

Kelin J. Kuhn, TED 2012
Carbon nanotubes do have metallic S/D

- One contact to 1 nm wide channel will be ~ 5.5 kOhm
- Short channel (15-40 nm) operates in the ballistic limit
- Type of metal defines p- or n-type channel

Franklin et al, Nature Nano 2010
Dark space in silicon / high-μ channels

- Dark space gets worse due to reduced DOS – $C_{inv} \propto \frac{1}{\text{DOS}}$
- Severe limiter for channel control ➰ SS / DIBL deterioration

Skotnicki & Boeuf, VLSI 2010

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Carbon Nanotubes have no dark space

- Current is confined to a single atomic layer
- Intimate channel control & low DOS
- Operation in the quantum capacitance limit (QCL) possible
- In QCL, the potential in channel is determined by the gate potential
- Short channel effects are suppressed
- Nanotube have no dopants

c.f. Knoch et al. EDL, 2008
Channels need high-k compatibility

Issues in high-k/metal gate stack

- Oxygen concentration control for prevention of EOT increase and oxygen vacancy formation in high-k
- Flat metal/high-k interface for better mobility
- Suppression of metal diffusion
- Suppression of oxygen vacancy formation
- Small interfacial state density at high-k/Si
- Control of interface reaction and Si diffusion to high-k
- Suppression of gate leakage current
- Endurance for high temperature process
- Oxygen diffusion control for prevention of EOT increase and oxygen vacancy formation in high-k
- Workfunction engineering for $V_{th}$ control
- Suppression of FLP
- Interface dipole control for $V_{th}$ tuning
- Remove contamination introduced by CVD
- Thinning or removal of SiO$_2$-IL for small EOT

Reliability: PBTI, NBTI, TDDB

H. Iwai, ULIS, 2012
Carbon Nanotubes are high-k compatible

- No dangling bonds
- Low chemical reactivity

High-k materials are easily employed

- Lanthanum oxide looks very promising

No dangling bonds

Low chemical reactivity
Si performance vs $L_{\text{gate}}$ and voltage scaling

<table>
<thead>
<tr>
<th>Structure</th>
<th>Bulk Planar</th>
<th>Tri-Gate 22nm</th>
<th>Tri-Gate NW</th>
<th>ETSOI</th>
<th>Bulk Planar</th>
<th>GAA NW</th>
<th>GAA NW</th>
<th>$\Omega$-gate NW</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{\text{g}}$ (nm)</td>
<td>35</td>
<td>30</td>
<td>30</td>
<td>14</td>
<td>22</td>
<td>20</td>
<td>35/25 (nFET/pFET)</td>
<td>22/30 (nFET/pFET)</td>
</tr>
<tr>
<td>Gate Dielectrics</td>
<td>Hf-based</td>
<td>Hf-based</td>
<td>SiO$_2$</td>
<td>HfO$_2$</td>
<td>HfO$_2$ ?</td>
<td>Hf-based</td>
<td>HfZrO$_2$</td>
<td>SiO$_2$</td>
</tr>
<tr>
<td>EOT (nm)</td>
<td>1</td>
<td>0.95</td>
<td>0.9</td>
<td>3</td>
<td>~1</td>
<td>-</td>
<td>1.5</td>
<td>-</td>
</tr>
<tr>
<td>$V_{\text{Th}}$ (V)</td>
<td>~0.4</td>
<td>~0.3</td>
<td>~0.2</td>
<td>-0.15 (nFET)</td>
<td>0.3~0.4</td>
<td>~0.3</td>
<td>0.3~0.4</td>
<td>~0.5</td>
</tr>
<tr>
<td>$V_{\text{DD}}$ (V)</td>
<td>1</td>
<td>1</td>
<td>0.8</td>
<td>1</td>
<td>1</td>
<td>0.9</td>
<td>1</td>
<td>1.1</td>
</tr>
<tr>
<td>$I_{\text{ON}}$ (mA/um)</td>
<td>1.36/1.07</td>
<td>1.53/1.23</td>
<td>1.26/1.1</td>
<td>0.83 (nFET)</td>
<td>1.65/1.25</td>
<td>1.2/1.05</td>
<td>0.83/0.95</td>
<td>2.05/1.5</td>
</tr>
<tr>
<td>DIBL (mV/V)</td>
<td>~150</td>
<td>~200</td>
<td>46/50</td>
<td>&lt;50</td>
<td>75/130</td>
<td>104/115</td>
<td>65/105</td>
<td>56/9</td>
</tr>
<tr>
<td>$SS$ (mV/dec)</td>
<td>-</td>
<td>~100</td>
<td>~70</td>
<td>&lt;80</td>
<td>&lt;90</td>
<td>87</td>
<td>85</td>
<td>&lt;80</td>
</tr>
</tbody>
</table>

- No data at low $V_{\text{ds}}$ (0.5V) and short $L_{\text{gate}}$
## III-V/Ge benchmark – only long Lgate

<table>
<thead>
<tr>
<th>Material</th>
<th>Planar (metal S/D, Strain, Buffer...)</th>
<th>FinFET</th>
<th>Tri-gate</th>
<th>Gate-all-around MOSFET</th>
<th>Nanowire</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>InGaAs</td>
<td>Ge</td>
<td>InGaSn</td>
<td>InGaAs</td>
<td>Ge</td>
</tr>
<tr>
<td>Dielectric /EOT</td>
<td>Al₂O₃/3.5 nm</td>
<td>7.6 Å</td>
<td>HfO₂+</td>
<td>5nm ALD Al₂O₃</td>
<td>5nm ALD Al₂O₃</td>
</tr>
<tr>
<td>Mobility</td>
<td>-</td>
<td>~600 (cm²/Vs)</td>
<td>5e12</td>
<td>200 h: 400 (µS/µm)</td>
<td>~700</td>
</tr>
<tr>
<td>Lch (nm)</td>
<td>55</td>
<td>W/L=30/5 µm</td>
<td>50 µm</td>
<td>100</td>
<td>4.5 µm</td>
</tr>
<tr>
<td>DIBL (mV/V)</td>
<td>84</td>
<td>-</td>
<td>-</td>
<td>180</td>
<td>-</td>
</tr>
<tr>
<td>SS (mV/dec)</td>
<td>105</td>
<td>-</td>
<td>150K</td>
<td>61pMOS</td>
<td>33nMOS</td>
</tr>
<tr>
<td>ION (µA/µm)</td>
<td>278 (V_D=0.5V)</td>
<td>3 (V_D=0.2V)</td>
<td>4 (n,p)</td>
<td>10 (V_D=0.5V)</td>
<td>400 (V_D=0.5V)</td>
</tr>
</tbody>
</table>

- No data at **low Vds (0.5V)** and **short Lgate**

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Sub-10 nm carbon nanotube transistor

Franklin, Nano Letters 2012

Operation at low $V_{ds}$ (0.4V) and short $L_{gate}$ of 9 nm

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Carbon nanotubes outperform alternatives

"Carbon nanotubes finally deliver"

InAs, MIT Alamo, Nature 2011
Si ITRS Alamo, Nature 2011
InGaAs, Intel, Nature 2011
CNT, IBM, Nano Letters 2012

Ioff = 100nA/µm
Vds = 0.5 V

CNT Ioff: 1000nA/µm for 9nm!
100nA/µm for >= 18nm

Jesus Alamo, Nature 2011
Advantage for CNTs in circuit designs

- CNT-based ICs can be designed as pass-transistor logic (PTL),
- Drawback of conventional Si-based PTL circuits—threshold voltage drop—is avoided in CNT PTL circuits
- Threshold voltage can be adjusted close to zero for p- and n-CNT FET (operation at Vdd= 1 and 0.4 V demoed)
- number of FETs & power greatly reduced / enhanced speed
- **Full adder**: instead of 28 FETs (in Si) only 6 CNT FETs


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Great News – how to proceed?

- Please give instructions
  - how to place billions of nanotubes with
    - one type of chirality
    - equal length
    - on a substrate
    - well aligned at some nanometer pitch
    - with a throughput of 120 wafers per hour

**Solution:** Just issue a purchase order for the new Applied Materials *Nano-Wonder™* machine

No - unfortunately – I am kidding
Placement strategies

- Grow in place or transfer
  - 95% semiconducting CNTs possible
    (Lei Ding et al, NL 2009)

- Aligned growth is possible – pitch not (yet) suitable
Placement strategies

- **Grow in place or transfer**
  - density can be increased by multiple growth

- Would work if growth length is > 300 /450 mm
  - Longest grown nanotube is 18.5 cm
  - Metallic could be eliminated (new methods)
  - Poor control over chirality

W Zhou et al., J. ACS Nano, 2011

Xueshen Wang et al, Nano Let. 2009
Placement strategies

- Use **self-assembly** to place nanotube
- Key ingredient: only *semiconducting* nanotubes
  - Bulk produced single-walled nanotubes (HiPCo etc)
  - Large-scale *single-chirality separation* of single-wall carbon nanotubes by simple gel chromatography or density gradient or DNA methods
  - Cloning of specific chirality - may be omitted
- Develop a *site specific selective binding* to deposit nanotubes at specific location
- Start *integration work* / *fabrication* of the devices
- Evaluate *(millions of)* devices
- Feedback and improve process – start again
Placement strategies

- Large-scale single-chirality separation of single-wall carbon nanotubes by simple gel chromatography

Huaping Liu et al., Nature Com, 2010
Placement strategies

- Single-chirality separation of single-wall carbon nanotubes by density gradient  
  Michael S. Arnold et al., Nature Nano, 2006
Placement strategies

- DNA sequence for structure-specific separation of carbon nanotubes.

X. M. Tu et al., Nature 2009

**Table 2 | Experimental conditions and quantification**

<table>
<thead>
<tr>
<th>Chirality (n,m)</th>
<th>Sequence</th>
<th>Dispersion solution*</th>
<th>Incubation period†</th>
<th>Yield‡ (µg per 100 µg)</th>
<th>Purity§ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(9,1)</td>
<td>(TCC)₁₀</td>
<td>0.1 M NaCl</td>
<td>None</td>
<td>0.1</td>
<td>80</td>
</tr>
<tr>
<td>(8,3)</td>
<td>(TTA)₃TTGT</td>
<td>0.1 M NaCl</td>
<td>1 day</td>
<td>0.1</td>
<td>70</td>
</tr>
<tr>
<td>(6,5)</td>
<td>(TAT)₄</td>
<td>0.1 M NaCl</td>
<td>None</td>
<td>0.5</td>
<td>90</td>
</tr>
<tr>
<td>(7,5)</td>
<td>(ATT)₄AT</td>
<td>0.1 M NaCl</td>
<td>None</td>
<td>0.2</td>
<td>90</td>
</tr>
<tr>
<td>(10,2)</td>
<td>(TATT)₂TAT</td>
<td>0.1 M NaCl</td>
<td>None</td>
<td>0.1</td>
<td>90</td>
</tr>
<tr>
<td>(8,4)</td>
<td>(ATTT)₃</td>
<td>0.1 M NaCl</td>
<td>None</td>
<td>0.3</td>
<td>90</td>
</tr>
<tr>
<td>(9,4)</td>
<td>(GTC)₂GT</td>
<td>0.1 M sodium acetate pH 4.5</td>
<td>2 days</td>
<td>0.5</td>
<td>60</td>
</tr>
<tr>
<td>(7,6)</td>
<td>(GTT)₃G</td>
<td>0.1 M NaCl</td>
<td>None</td>
<td>0.4</td>
<td>90</td>
</tr>
<tr>
<td>(8,6)</td>
<td>(GT)₆</td>
<td>0.1 M NaCl</td>
<td>1 day</td>
<td>0.8</td>
<td>90</td>
</tr>
<tr>
<td>(9,5)</td>
<td>(TGTT)₂TGT</td>
<td>0.1 M NaCl, 10% glycerol</td>
<td>None</td>
<td>0.3</td>
<td>70</td>
</tr>
<tr>
<td>(10,5)</td>
<td>(TTTA)₃T</td>
<td>0.1 M sodium acetate pH 4.5</td>
<td>2 days</td>
<td>0.5</td>
<td>90</td>
</tr>
<tr>
<td>(8,7)</td>
<td>(CCG)₂CC</td>
<td>0.1 M NaCl, 10% glycerol</td>
<td>None</td>
<td>0.4</td>
<td>80</td>
</tr>
</tbody>
</table>
Placement strategies

- Cloning of a specific chirality

Chirality-pure seeds from DNA-based separation

- Semiconducting SWCNT
- Metallic SWCNT

Deposition of the seeds

Air annealing and water vapour annealing

Vapour-phase epitaxy

Nanotube cloning with controlled chirality

Jia Liu et al., Nature Com 2012

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Placement strategies

- Site specific selective binding to deposit nanotubes

Hongsik Park et al., Nature Nano 2012
Placement strategies  

- Site specific selective binding to deposit nanotubes
  - 200 nm pitch in the x-direction
  - 500 nm pitch in the y-direction
  - 10^9 sites/cm^2 density (scale bar, 400 nm).
  - Precise placement in two dimensions
  - 90% of the trenches contain at least one nanotube

Trench density = 10^9 cm^-2
Placement strategies  

- **Fabricate devices at** the CNT-filled trenches

- **More than 10,000 devices** have been fabricated over the *pre-patterned trenches* with CNT-selfassembly by ion-exchange reaction

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Placement strategies  Hongsik Park et al., Nature Nano 2012

- Evaluation of more than 10,000 CNT devices

- This is an amazing result – given that 2 people have worked on the topic for a couple of month
Just compare – for a moment - with Si

- **Evaluation of more than 1 million CMOS FETs**

  Tsunomura et al. Jpn. JAP (2009)

  - gate length is **60 nm** and
  - gate width is **140 nm**

- Compared with mature Si-technology - CNT assembly is not too bad

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Summary

- Opportunity window for alternative channel materials is closing
- Performance-wise carbon nanotube devices outperform any alternative
- Huge gap for industrial integration exists
- A possible roadmap exists based on self-assembly
- The low-hanging fruits for nanotube device research are gone
- What remains is hard work to make it happen – not ideally suited for academia