Near-term emerging computing technologies

1. Carbon-based computing: carbon-nanotubes and graphene transistors
2. Single electron devices
3. Quantum dots and quantum cellular automata
4. 3D integrated circuits
5. Integrated photonic networks
1. Carbon-based Computing

2D graphene sheet

bucky ball
CNT
3D graphite

[source: Geim and Novoselov ‘07]
1. Allotropes of carbon

Some allotropes of carbon: a) diamond; b) graphite; c) lonsdaleite; d–f) fullerenes (C60, C540, C70); g) amorphous carbon; h) carbon nanotube.
1A. Carbon nanotubes

- Most single-walled nanotubes (SWNT) have a diameter of close to 1 nm, with a tube length that can be many thousands of times longer.

- The structure of a SWNT can be conceptualized by wrapping a one-atom-thick layer of graphite called graphene into a seamless cylinder.
1A. CNT structure

- The structure of a nanotube strongly affects its electrical properties. Depending on the chirality and width of the tube, it could be either a metallic or semiconductor. In theory, metallic nanotubes can have an electrical current density more than 1,000 times greater than metals such as silver and copper. It is predicted that carbon nanotubes will be able to transmit up to 6000 watts per meter per kelvin at room temperature; compare this to copper, a metal well-known for its good thermal conductivity, which only transmits 385 $W \cdot m^{-1} \cdot K^{-1}$. 

[Source: Avouris, IBM]
CNT FET

Advantages:
• Speed
• Size
• Thermal conductivity

Current problems:
• No good device reproducibility
• Yield
• No higher methods of integration
1B. Graphene transistors

The electrons in graphene behave as if they have no mass. Like photons—but unlike electrons in other materials—the electrons move at a constant speed, regardless of how much energy each one has. At room temperature electrons in graphene move at 200,000 centimeters per second for every volt per centimeter of electric field, 100 times faster than in silicon.

A transistor built out of graphene, therefore, should operate much faster than a comparable one made from silicon.

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Thin ribbons of graphene (left) (scale bar is 100 nanometers). Graphene is made of carbon atoms arranged in hexagons (right).

[source: Hongjie Dai]

[source: Avouris ‘08]
2. Single Electron Devices

Single Electron Tunneling (SET) devices consist of one or several conducting islands, separated from each other and from external electrodes by tunnel junctions (or capacitors)

According to the laws of classical electrodynamics, no current can flow through an insulating barrier. According to the laws of quantum mechanics, there is a non-vanishing probability for an electron on one side of the barrier to reach the other side

\[ \text{Likharev '99} \]
2. Single electron devices

- Current flow through a tunnel junction is a series of events in which exactly one electron passes (tunnels) through the tunnel barrier.
- The tunnel junction capacitor is charged with one elementary charge by the tunnelling electron, causing a small voltage buildup. If the capacitance is very small, the voltage buildup can be large enough to prevent another electron from tunnelling.
- The increase of the differential resistance around zero bias is called the Coulomb blockade.
- The temperature has to be low enough so that the characteristic charging energy is larger than the thermal energy of the charge carriers. For capacitances above 1 fF, the temperature has to be below about 1 kelvin.
2. Single electron devices

![Image of single electron transistor](source-image)

**Advantages:**
- High density
- Low power

**Challenges:**
- Room temperature operation
- Noise
- Lack of drive current

[Source: wikipedia]
3. Quantum Cellular Automata (QCA)

- Quantum dots are nanometer-sized semiconductor crystals with size-dependent optical, physical, electronic and chemical properties.
- Quantum dots use the arrangements of individual electrons, instead of currents and voltages, to encode binary information.
- A QCA cell consists of four quantum dots.
- When the cell is charged with two excess electrons, they occupy diagonal sites as a result of mutual electrostatic repulsion.

Possible polarization of a QCA cell:
3. QCA gates

QCA majority gate

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In QCA, each cell responds to the polarization of the neighboring cells

Disadvantages:
- Limited fanout
- Architecture
4. 3D integrated circuits

- Optical lithography is approaching its natural limits → 3D integration can extend Moore’s law by going vertically

- Advantages:
  - Form factor
  - Heterogeneous integration
  - Better performance

[from future-fab.com]
4. 3D IC manufacturing

1. **Blind TSV vias**, which do not go all the way through the wafer, are created in the wafer either while the transistors are being made or immediately after.

2. TSV vias are *coated* with a layer of *insulating material* before *copper* is *deposited*.

3. Wafer is *thinned* from the back until the TSV vertical wires are exposed; the next wafer can be *bonded* to the back of the thinned wafer, *front-to-back*.
4. Challenges for 3D ICs

- Heat
- Yield and Testing

3D DRAM Memory

3D processor
5. Computing with light: photonics

**Objective:** eliminate memory bandwidth and latency problems by replacing metal wires and electrons with photons and beam of lights

Main ingredients for a silicon-based photonic network. Data transfers of about 30-100 GB/s.

[source: intel.com]