Carbon-based Resistive Memory


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Outline of Presentation

• Introduction and Motivation
• Basic Switching in Carbon
• Carbon Allotropes
• Carbon Nanotubes
• Graphene-like Conductive Carbon
• Insulating Carbon
• Conclusions
Introduction and Motivation

• **Resistive Memories** like
  – *Phase Change* (Ge$_x$Sb$_y$Te$_z$,.... )
  – *Nano-ionic*, (CBRAM-like, e.g. Ag$_2$S, Ag-GeSe, Cu$_2$S....)
  – *Transition-Metal-Oxide* (NiO, TiO$_2$,.....)
  *are very promising memory technologies*

• but are binary, ternary or even more complex materials:
  – what about **scalability**
  – how do they respond to **volume/surface ratio**
  – what about **variability**, if scaled

• **Are there other, simpler materials available?**
Introduction and Motivation

• The available current in a memory cell is given by the select device (FET, diode)

An upper limit may be estimated by:

\[ j = e \cdot N_d \cdot v_{sat} = e \cdot 10^{19} \cdot 10^7 = 16 \text{ MA/cm}^2 \]

• Typical currents in phase change memories are \(~10 \text{ MA/cm}^2\)

Are there options or materials which enable switching at low currents (some \(\mu\text{A}\))?
Introduction: Carbon Memory

- **sp³**
  - Low conductance
  - sp² to sp³ conversion of disordered graphitic carbon (phase change of carbon)

- **sp²**
  - High conductance
  - Inherently scalable to atomic scale (no phases of different materials)
Basic Switching in Carbon

- Current changes **structure** and **resistance**
- Resistance changes by a factor of ~ 100
- **High** ➔ **Low** well known from e-fuses
- **New**: switch to disorder by short pulse

TEM image by courtesy of J. Huang et al., Nano Letters 2006 Vol. 6, No. 8 pp. 1699-1705

F. Kreupl et al.
Short Laser Pulses on Graphite

- Short laser pulse induces disorder (D-band)
- D-band overlaps with sp³-peak at 1332 cm⁻¹
- Diamond cubic phase observed by e-beam diffraction

⇒ Disordered, quenched state by short energy pulse


F. Kreupl et al.
3 ps Laser Pulse on Graphite

- The shorter the laser pulse the more disorder
  ➔ Disordered, quenched state by short energy pulse


F. Kreupl et al.
Short Energy Pulses

• Fluence of the laser pulse at graphite ablation threshold = ~ 285 mJ/cm²

  K. Sokolowski-Tinten et al., CLEO 2000

Energy density (energy/volume) = \(95 \text{ KJ/cm}^3\)

• Energy density for a wire subjected to a current:

  \[ E/V = j^2 \rho t = 1\text{GA/cm}^2 \cdot 1\text{m\Omega cm} \cdot 20 \text{ ns} = 2 \text{ MJ/cm}^3 \]

\(\Rightarrow\) Disordered, quenched state by short current pulse
Short Current Pulse

temperature distribution in carbon filament after 1 ns current pulse with 1.7 GA/cm²:

$T_{\text{peak}} \sim 3900 \text{ K}; \text{ rapid cool down (0.05 ns)}$
Carbon Nanotubes

• Nanotubes have a **length dependent** switching current
• **25 nm** long tubes need ~ **100µA @ 1.5 V** and have no phonon-limited transport
• tubes > **200 nm** need ~ **30 µA @ 4V** (phonon-limited)

⇒ Select device needs to handle ~ **30 µA** and **4-8 Volt**
Carbon Nanotubes
In vacuum ~ 12 µA current possible

on-state  off-state  switch on  on-state
12 uA    6 uA, 1.6V

Jin et al., nature 18 nanotechnology | VOL 3 | JANUARY 2008 |
Allotropes of Carbon (investigated)

- **Carbon Nanotubes**
  - sp²-type
  - difficult to integrate
  - high conductivity

- **Graphene or Conductive Carbon**
  - sp²-type
  - easy to integrate
  - high conductivity

- **Insulating carbon**
  - sp³-type, diamond-like
  - easy to integrate
  - high resistivity

source: J. Robertson
Conductive Carbon (CC)

- Conductive Carbon is
  - graphene-like
  - easily deposited (CVD)
  - can be used as interconnect material (highly conductive)
  - easy to pattern


Conductive Carbon: Memory Cell

- Carbon memory cells with varying diameter
Conductive Carbon: Critical Current

- Critical current density of 350 MA/cm² observed
- Appropriate cell diameter ~ 6 nm for I < 100 μA
  ➔ Use spacer, cladding or self-assembled nano-pores
Conductive Carbon (CC): Switching

- Shmoo-plot of 40 nm diameter CC memory cell
  - smaller diameter, current compliance and optimized pulses required
Insulating Carbon (IC): Memory Cell

- Insulating diamond-like carbon film
- First switching occurs now from high to low state
Insulating Carbon (IC): Critical Field

- Quasi-static switching curves determine critical field
- Switching power is about 50µW with leakage currents.
- Very low power levels: 5 µA @ 1.5 V (P= 7.5 µW)
• Read endurance at 75 degree C: $2.3 \times 10^{13}$ read cycles at 0.1 V.

• Switching speed is faster than 11 ns.
Insulating Carbon: Switching

- I(V) curves show similar behavior after pulses
- Resistance level can be trimmed by individual voltage pulses (multi-level capability)
Insulating Carbon: Filament size

10 V pulse evaporates metal $\rightarrow$ filament $\sim 10$ nm @ 10 V $\rightarrow$ use carbon as current spreader
Conclusions

• **New carbon memory** proposed based on \( \text{sp}^2 \) to \( \text{sp}^3 \) conversion

• Inherently **fast**: reset \( \sim \) ns, set \( \sim \) ns

• **Nanotubes** need \( \sim 30 \ \mu\text{A} \) @ 8V

• **Graphene-like Conductive Carbon** needs pores \(< 6 \ \text{nm}\)

• **Insulating Carbon** shows lowest switching power: \( 5 \ \mu\text{A} \) @ 1.5 V (P= 7.5 \( \mu\text{W}\))

• **Pulses and cell design** needs to be optimized

• **Should also work with Fullerens, Graphene and Diamonds**
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Questions?

Thank you!