Carbon-based Resistive Memory

Franz Kreupl, Rainer Bruchhaus[+], Petra Majewski , Jan B. Philipp, Ralf Symanczyk, Thomas Happ*, Christian Arndt*, Mirko Vogt*, Roy Zimmermann*, Axel Buerke*, Andrew P. Graham*, Michael Kund

Qimonda AG,

[+]Qimonda North America,

**Qimonda Dresden GmbH & Co. OHG*

franz.kreupl@qimonda.com

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* ($Ge_xSb_yTe_z$,....)**
  - ***Nano-Ionic, (*CBRAM-like, e.g. Ag_2S, Ag-GeSe, Cu_2S....)**
  - ***Transition-Metal-Oxide* (NiO, TiO_2,.....)**

  are very promising memory technologies

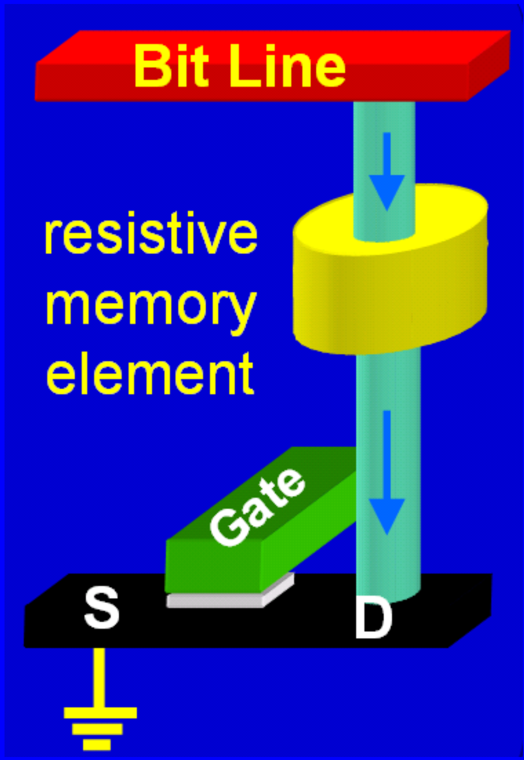
- **but are binary, ternary or even more complex materials:**
  - **what about scalability**
  - **how do they respond to volume/surface ratio**
  - **what about variability, if scaled**
- **Are there other, simpler materials available?**

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:

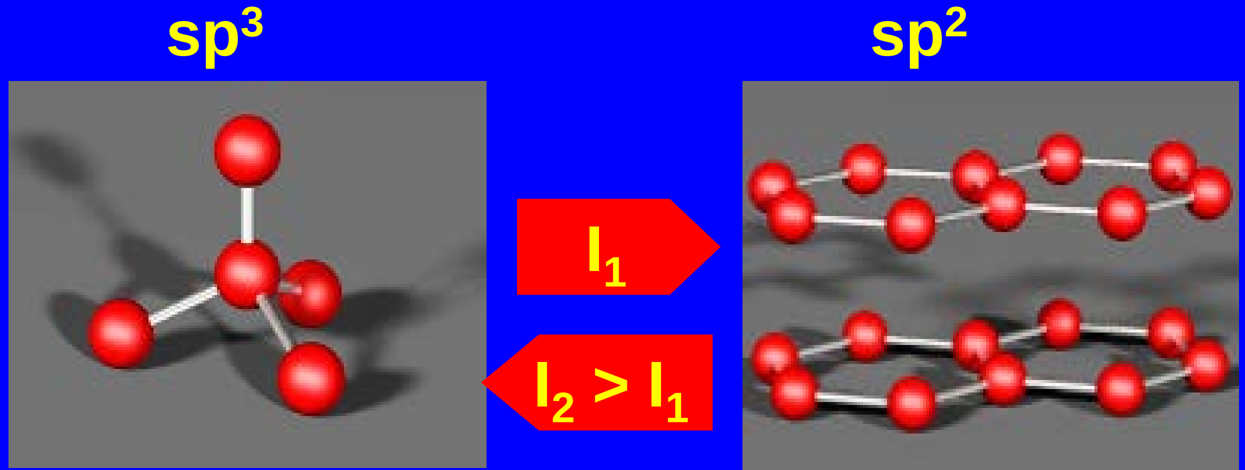
  $j = e_* N_{d*} v_{sat} = e_* 10^{19}{}_* 10^{7} = 16\ \mathrm{MA/cm^2}$



- Typical currents in phase change memories are ~10 $\mathrm{MA/cm^2}$

Are there options or materials which enable switching at low currents (some µA)?

Introduction: Carbon Memory



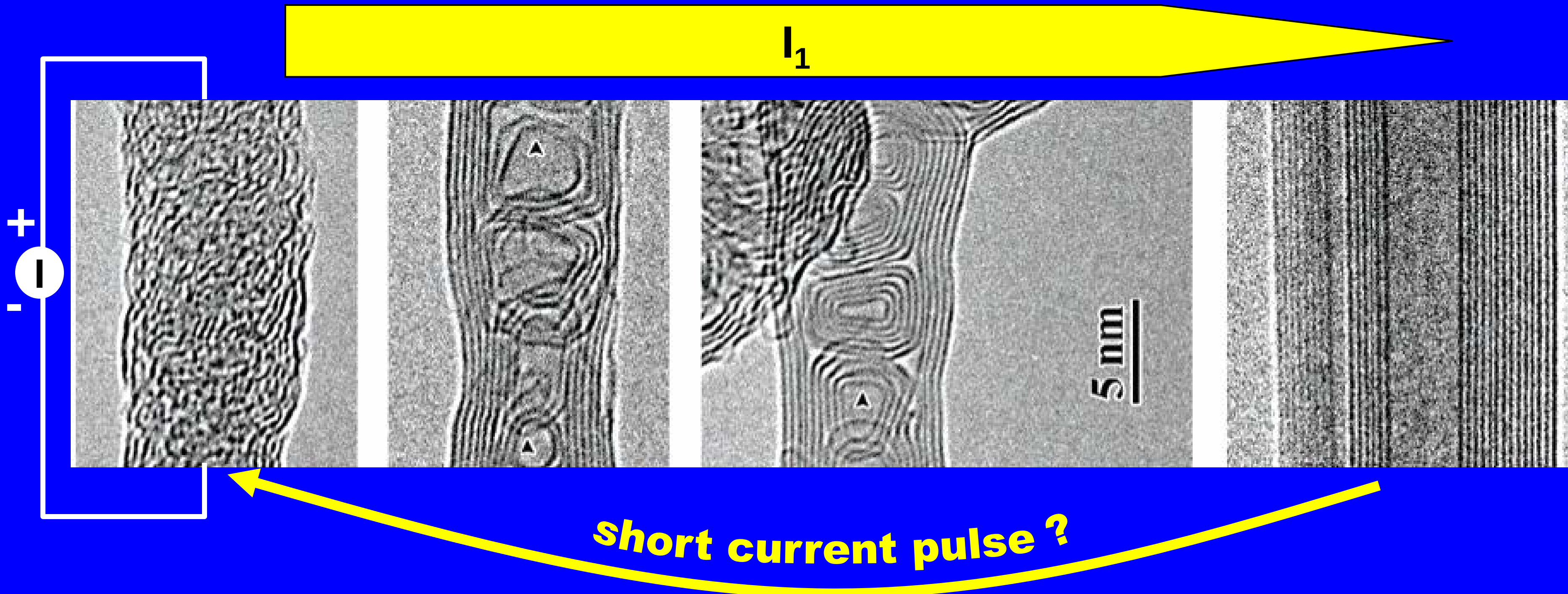
low conductance

high conductance

- **sp^2 to sp^3 conversion of disordered graphitic carbon (phase change of carbon)**
- **inherently scalable to atomic scale (no phases of different materials)**

F. Kreupl et al.

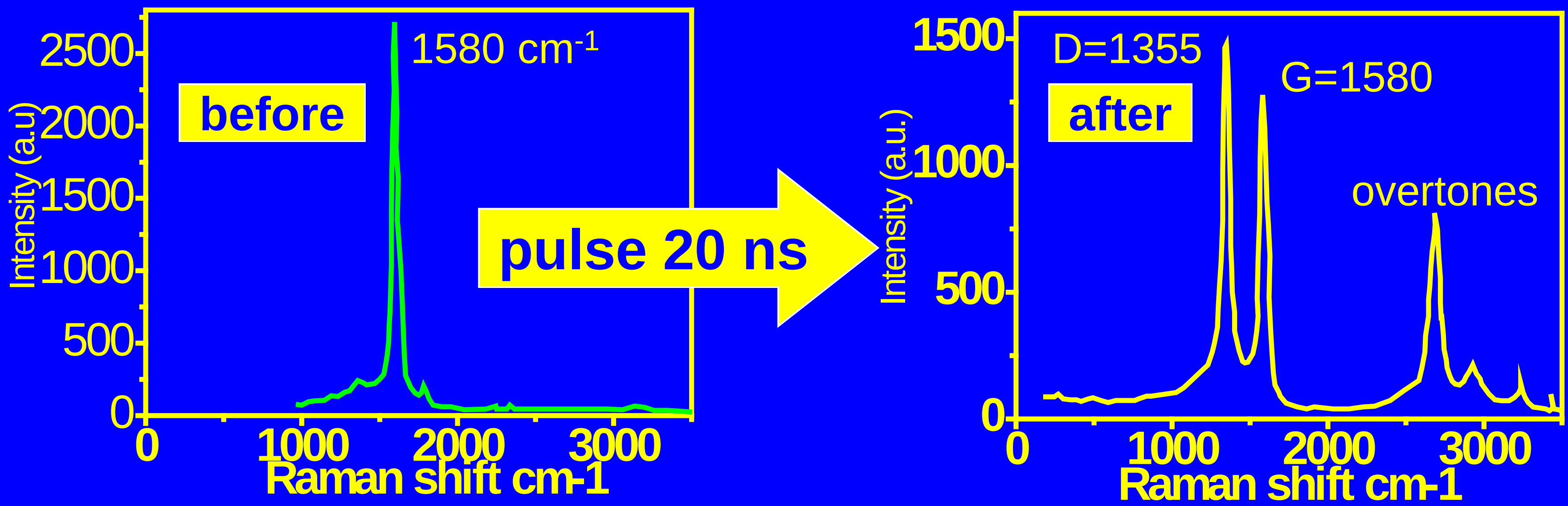
Basic Switching in Carbon



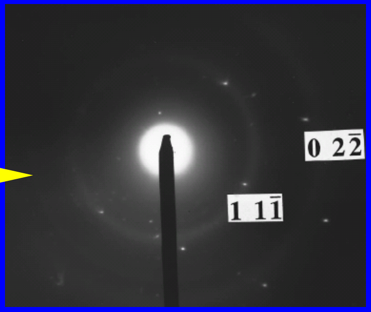
- Current changes **structure** and **resistance**
- Resistance changes by a factor of ~ 100
- **High → Low** well known from e-fuses
- **New: switch to disorder by short pulse**

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

Short Laser Pulses on Graphite



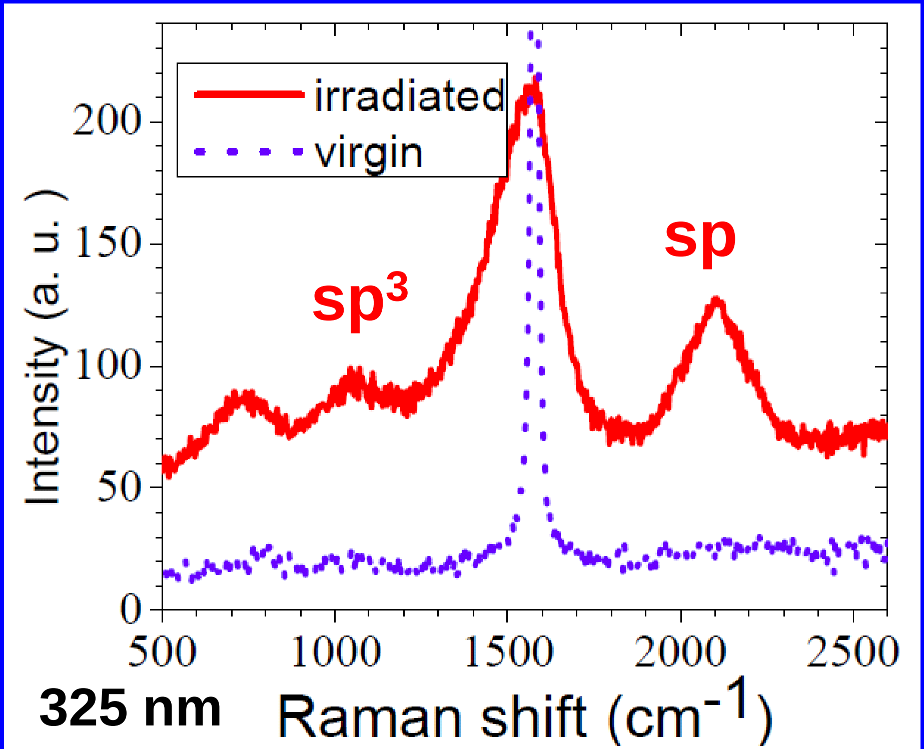
- **Short laser pulse induces disorder (D-band)**
- **D-band overlaps with sp^3-peak at 1332 cm^{-1}**
- **Diamond cubic phase observed by e-beam diffraction**

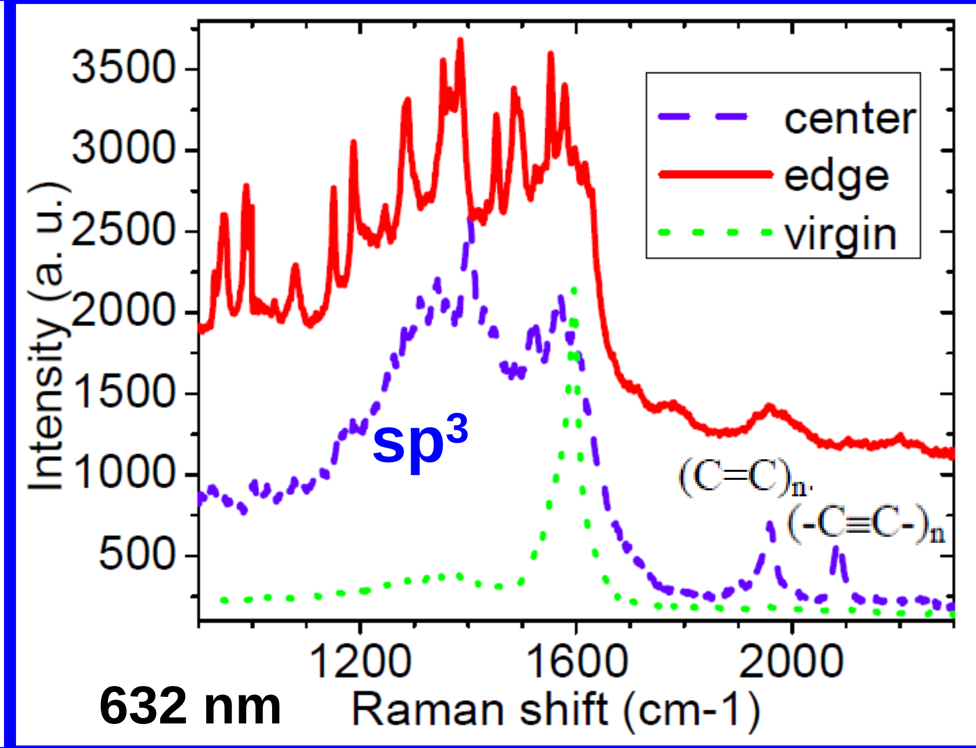


➔ Disordered, quenched state by short energy pulse

Bonelli et al., Laser-irradiation-induced structural changes on graphite, Phys. Rev. B 59, 13513 (1999)

3 ps Laser Pulse on Graphite





- **The shorter the laser pulse the more disorder**

➔ Disordered, quenched state by short energy pulse

source: Anming Hu, PhD Thesis, U Waterloo, 2008

Short Energy Pulses

- **Fluence of the laser pulse at graphite ablation threshold =~ 285 mJ/cm^2**

  K. Sokolowski-Tinten et al., CLEO 2000

  Energy density (energy/volume) = 95 KJ/cm^3

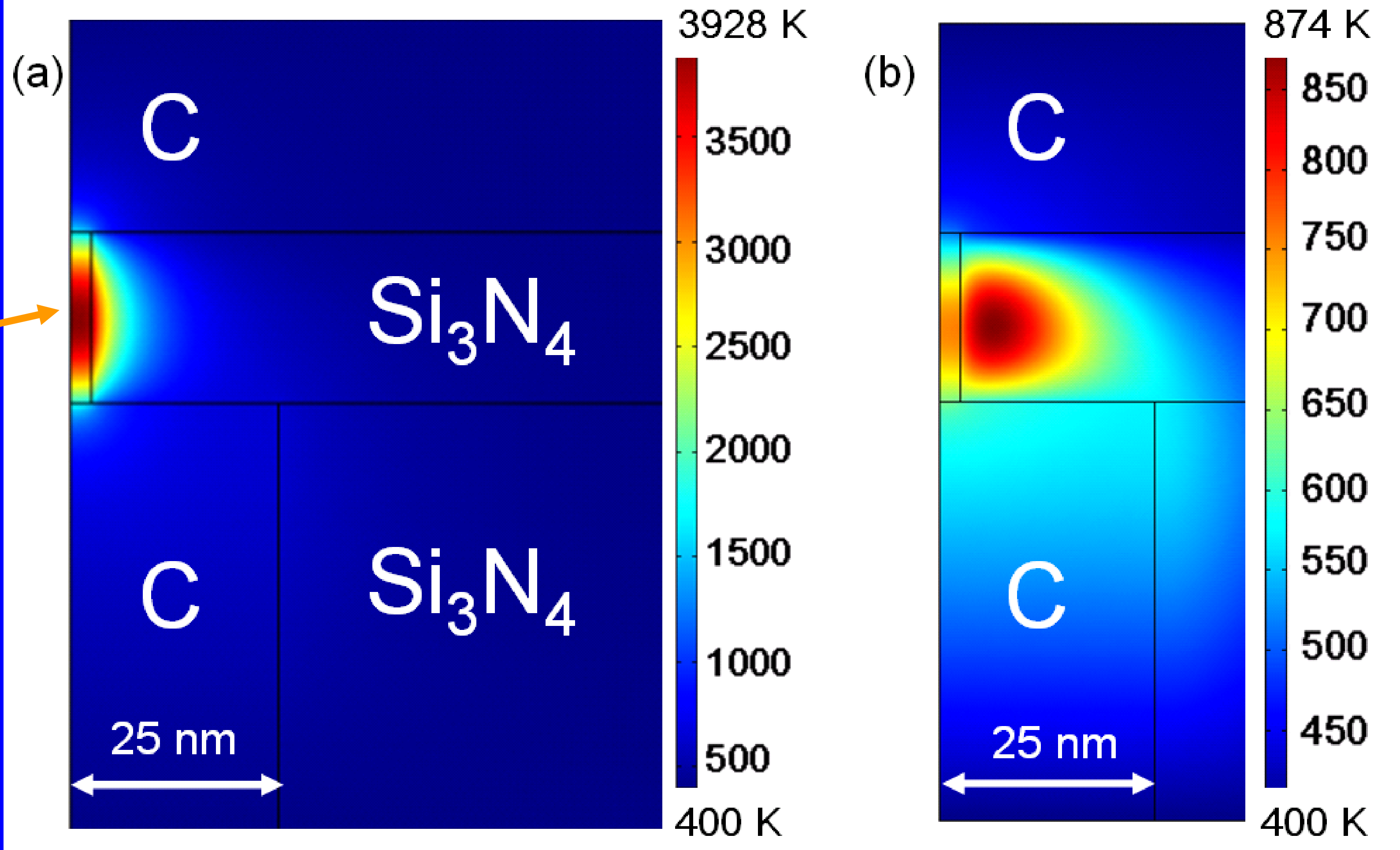
- **Energy density for a wire subjected to a current:**

  $E/V = j^2\rho t$ = 1GA/cm^2 ·1mΩcm · 20 ns = 2 MJ/cm^3

➔Disordered, quenched state by short current pulse

Short Current Pulse

carbon cell

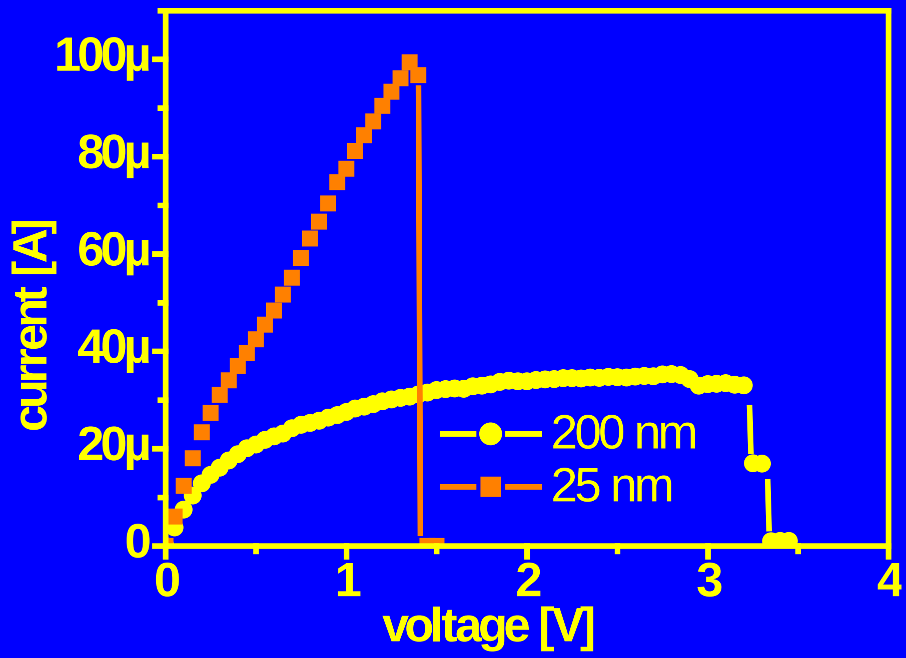


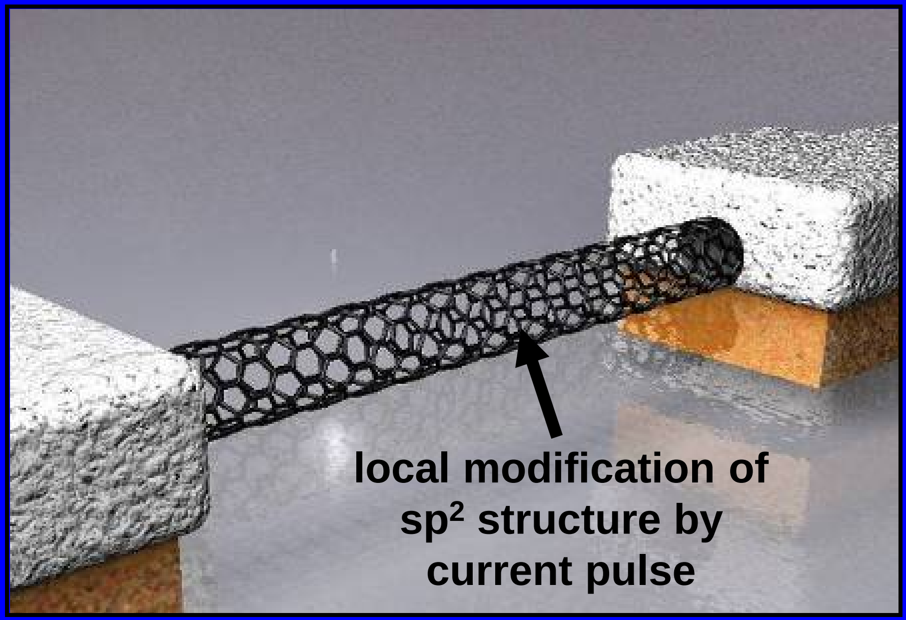
temperature distribution in carbon filament after 1 ns current pulse with 1.7 GA/cm^2 :

T_{peak} ~ 3900 K; rapid cool down (0.05 ns)

F. Kreupl et al.

Carbon Nanotubes





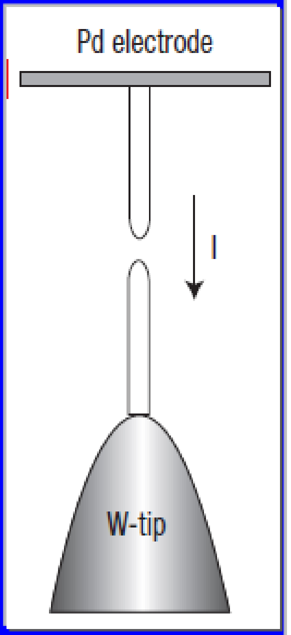
- Nanotubes have a **length dependent** switching current
- **25 nm** long tubes need ~ **100µA @ 1.5 V** and have no phonon-limited transport
- tubes **> 200 nm** need ~ **30 µA @ 4V** (phonon-limited)

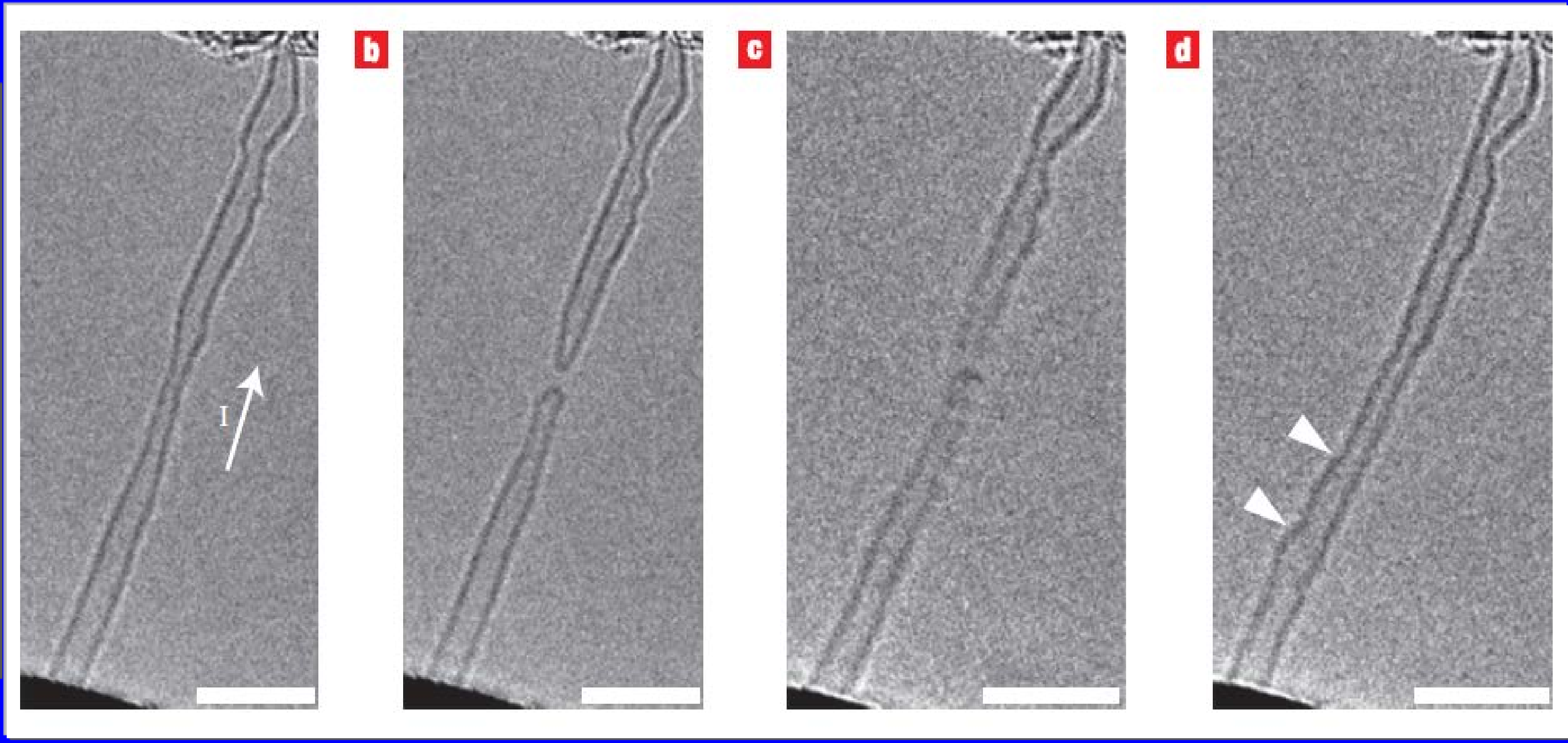
➔ **Select device needs to handle ~ 30 µA and 4-8 Volt**

F. Kreupl et al.

Carbon Nanotubes

In vacuum ~ 12 µA current possible



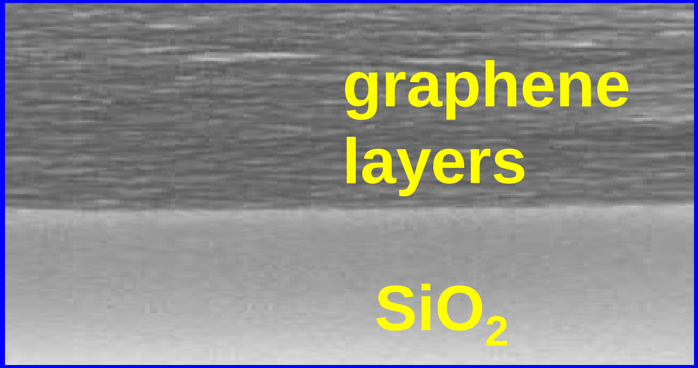


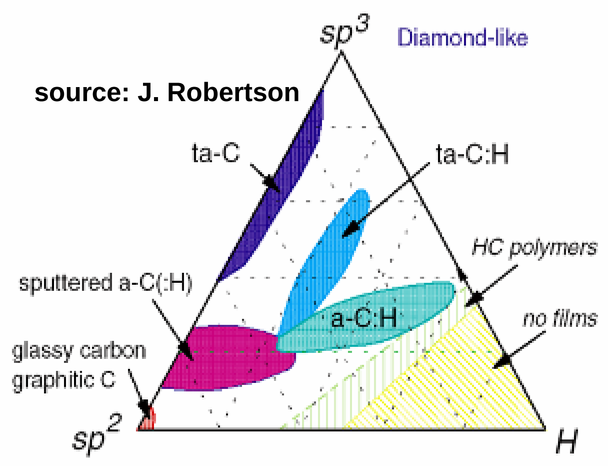
on-state **off-state 12 uA** **switch on 6 uA, 1.6V** **on-state**

Jin et al., nature 18 nanotechnology | VOL 3 | JANUARY 2008 |

Allotropes of Carbon (investigated)

- **Carbon Nanotubes**
  - sp^2-type
  - difficult to integrate
  - high conductivity
- **Graphene or Conductive Carbon**
  - sp^2-type
  - easy to integrate
  - high conductivity
- **Insulating carbon**
  - sp^3-type, diamond-like
  - easy to integrate
  - high resistivity

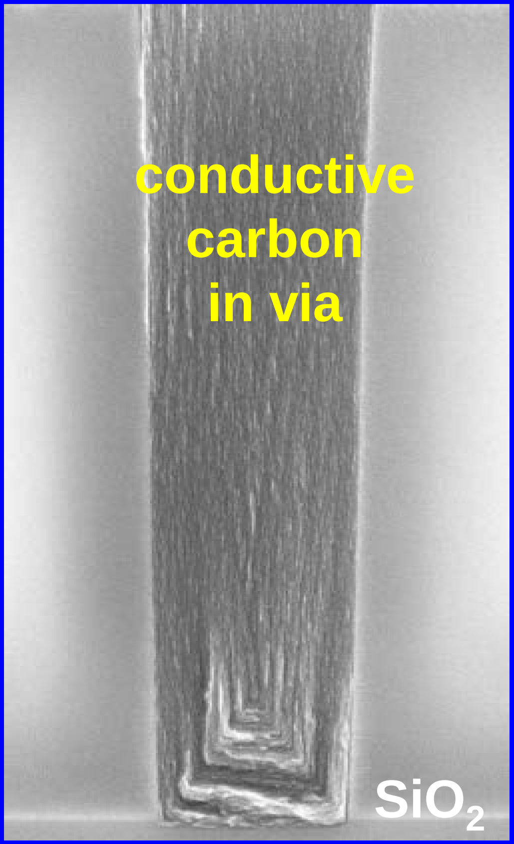




F. Kreupl et al.

Conductive Carbon (CC)

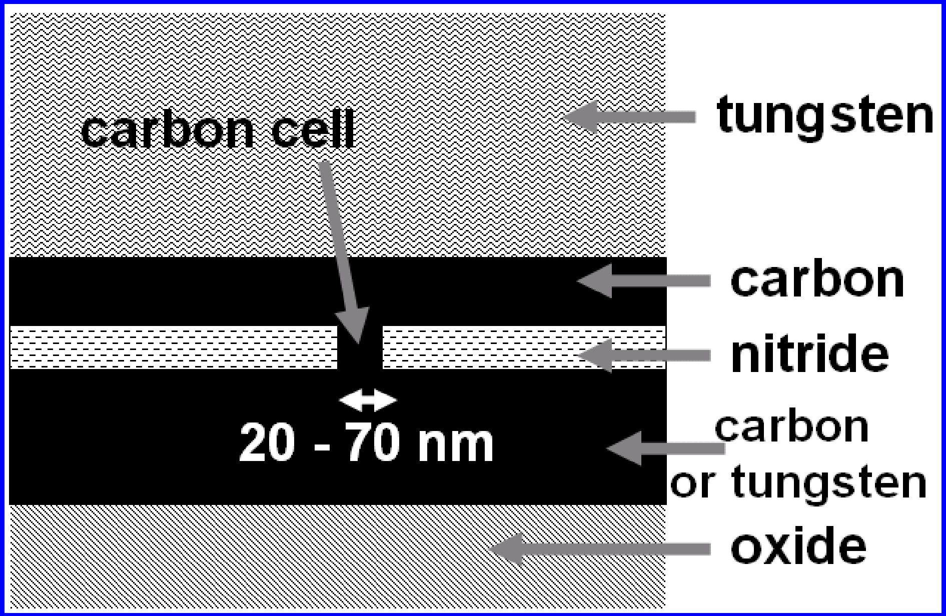
- Conductive Carbon is
  - graphene-like
  - easily deposited (CVD)
  - can be used as interconnect material (highly conductive)
  - easy to pattern

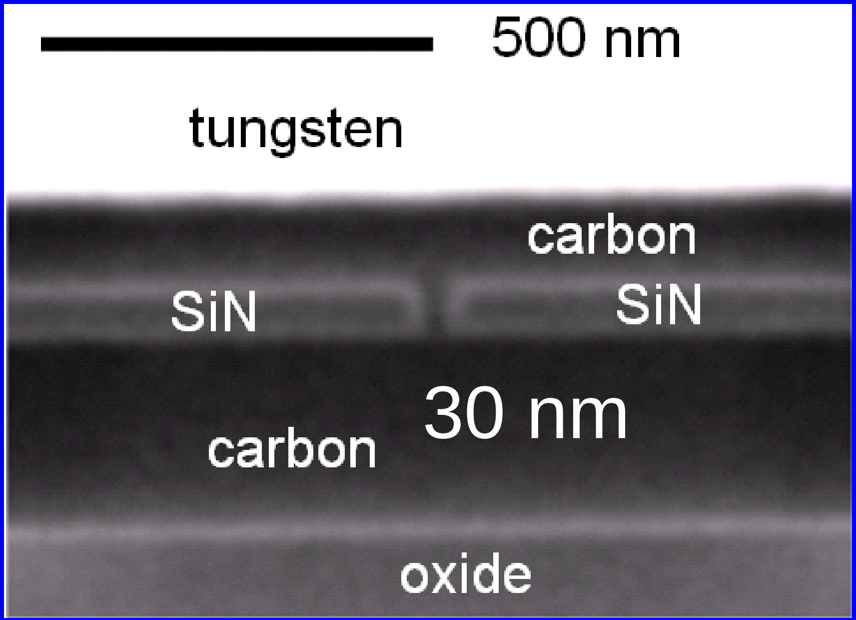


R. Seidel. et al., Chemical Vapor Deposition Growth of Single-Walled Carbon Nanotubes at 600 °C and a Simple Growth Model *J. Phys. Chem. B*, (2004)

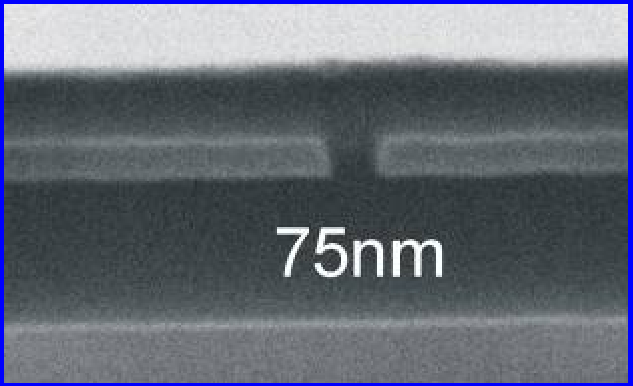
G. Aichmayr et al., Carbon-high-k Trench Capacitor for the 40nm DRAM Generation, VLSI Technology, (2007)

Conductive Carbon: Memory Cell



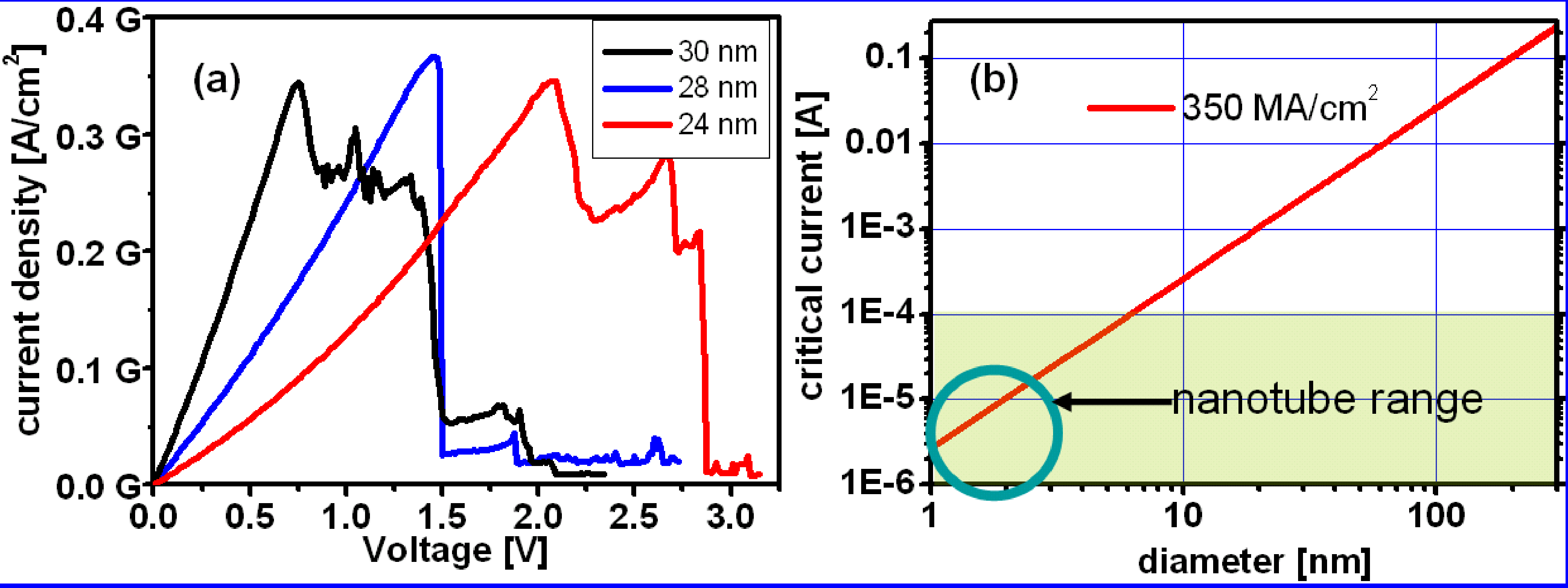


- **Carbon memory cells with varying diameter**



F. Kreupl et al.

Conductive Carbon: Critical Current

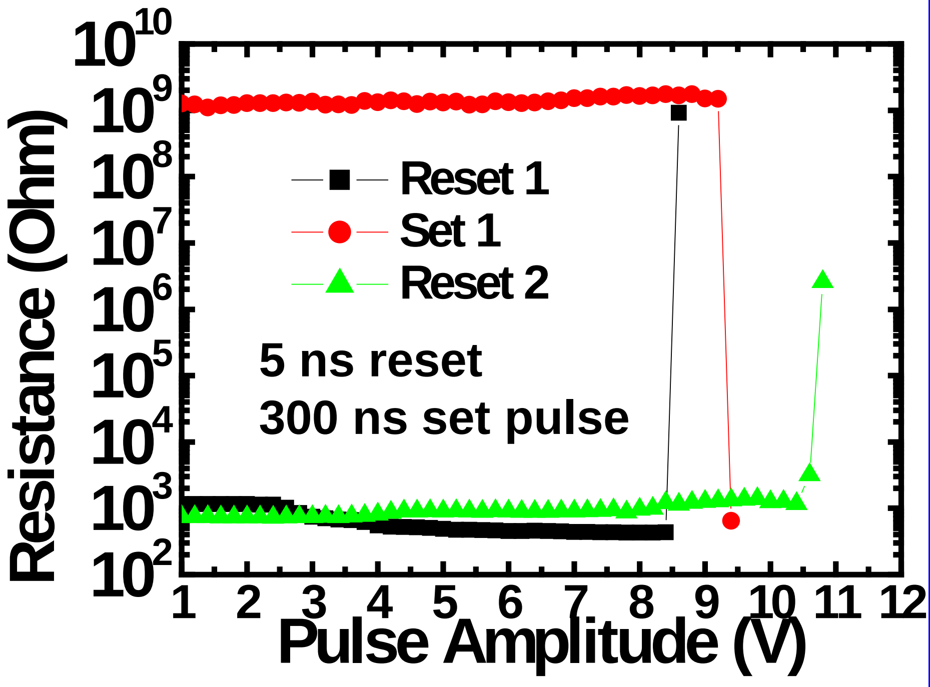


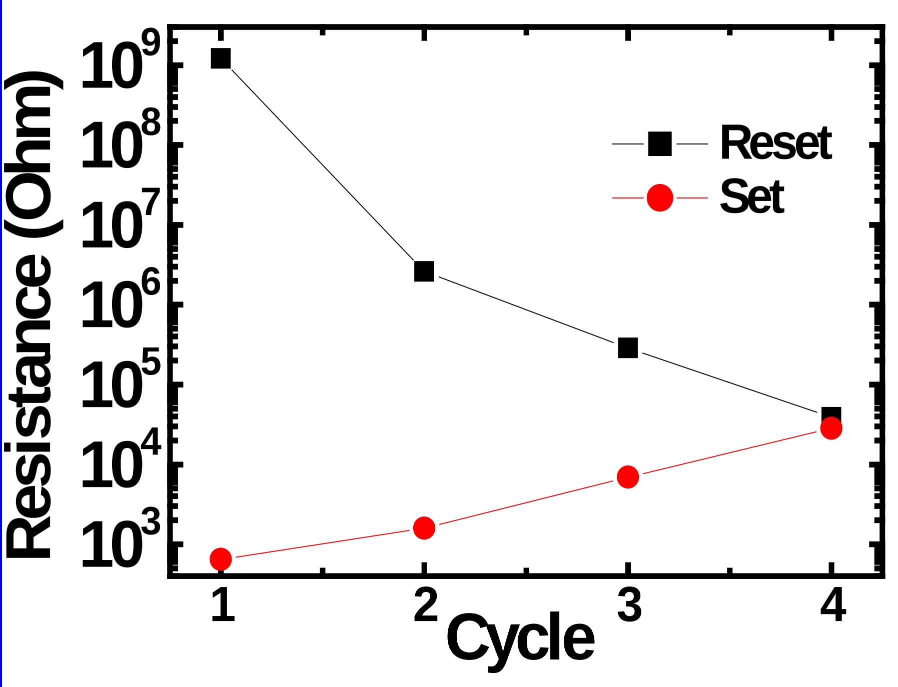
- **Critical current density of 350 MA/cm² observed**
- **Appropriate cell diameter ~ 6 nm for I < 100 µA**

➔ Use spacer, cladding or self-assembled nano-pores

F. Kreupl et al.

Conductive Carbon (CC): Switching



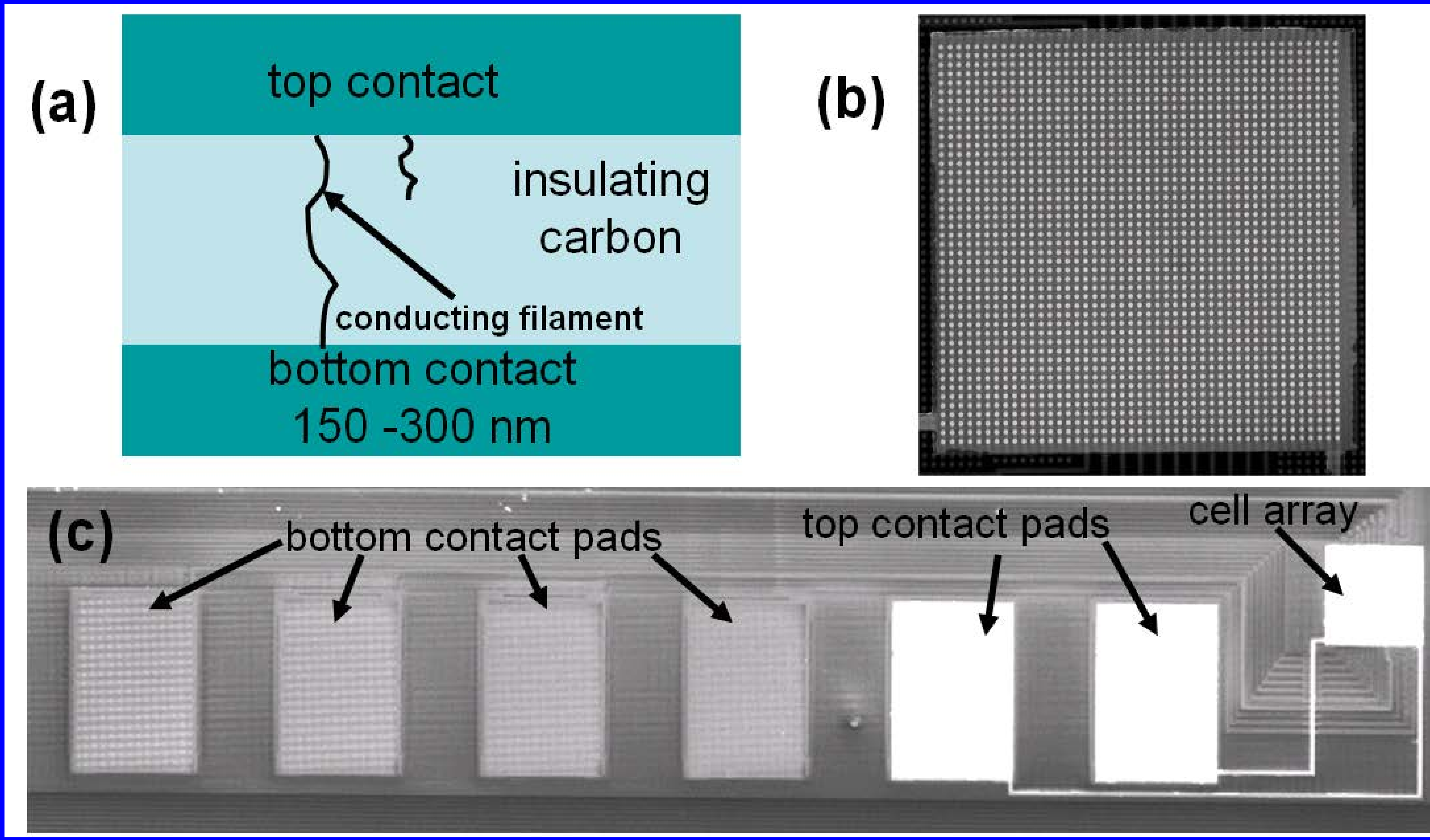


- **Shmoo-plot of 40 nm diameter CC memory cell**

➔ smaller diameter, current compliance and optimized pulses required

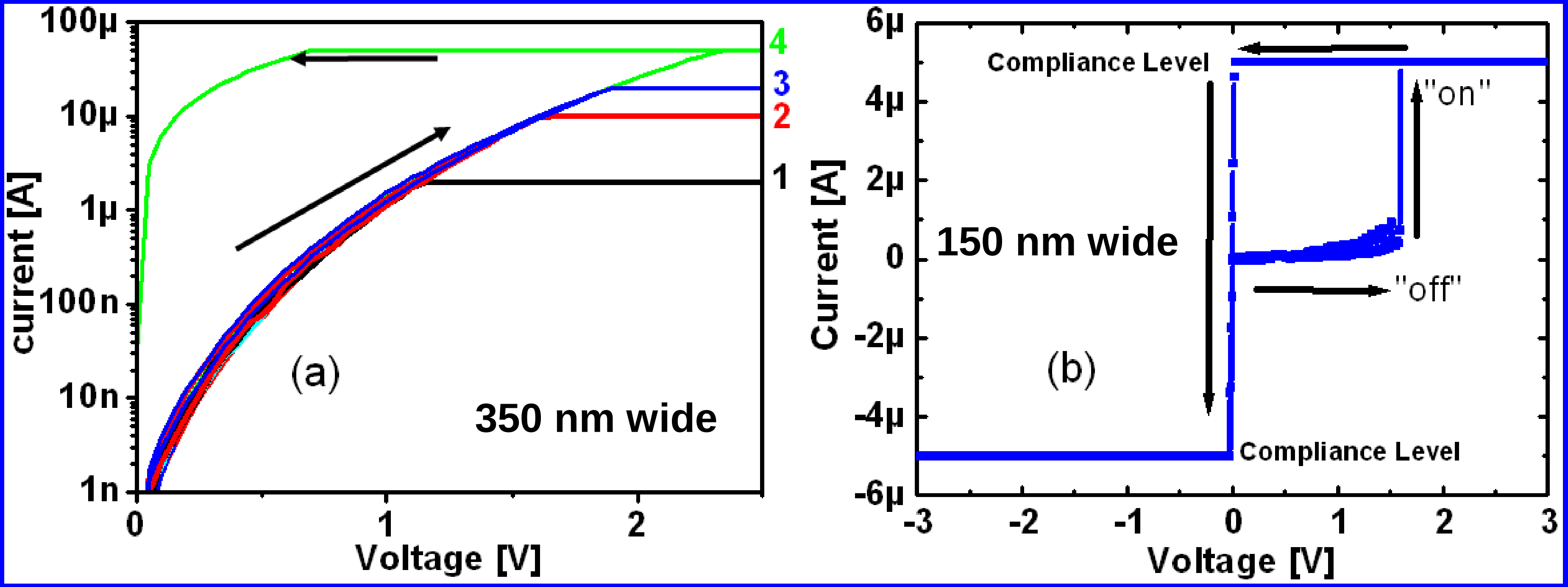
F. Kreupl et al.

Insulating Carbon (IC): Memory Cell



- **Insulating diamond-like carbon film**
- **First switching occurs now from high to low state**

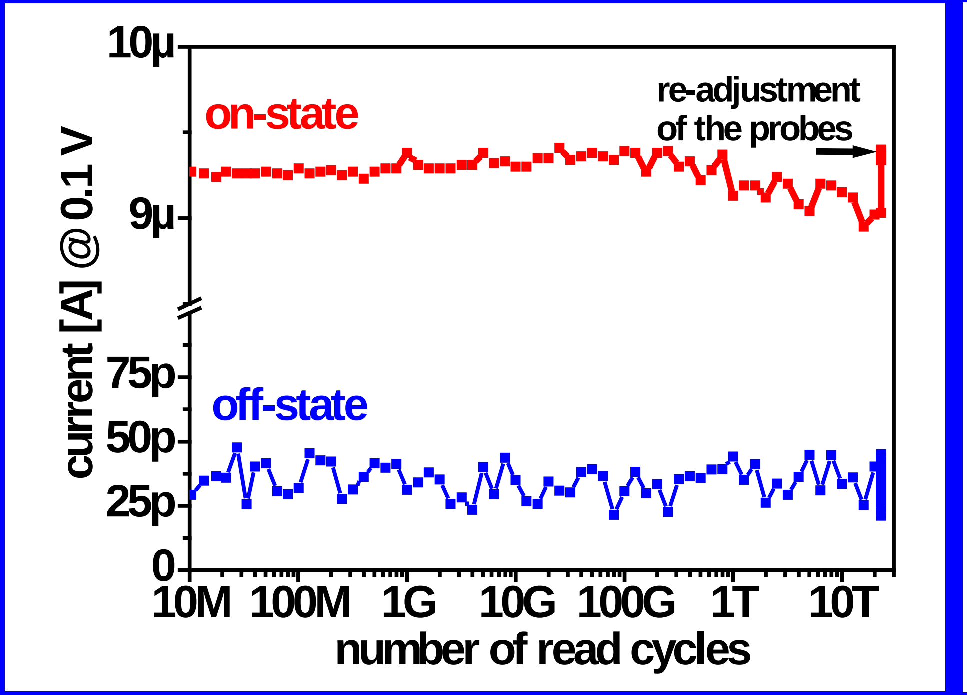
Insulating Carbon (IC): Critical Field

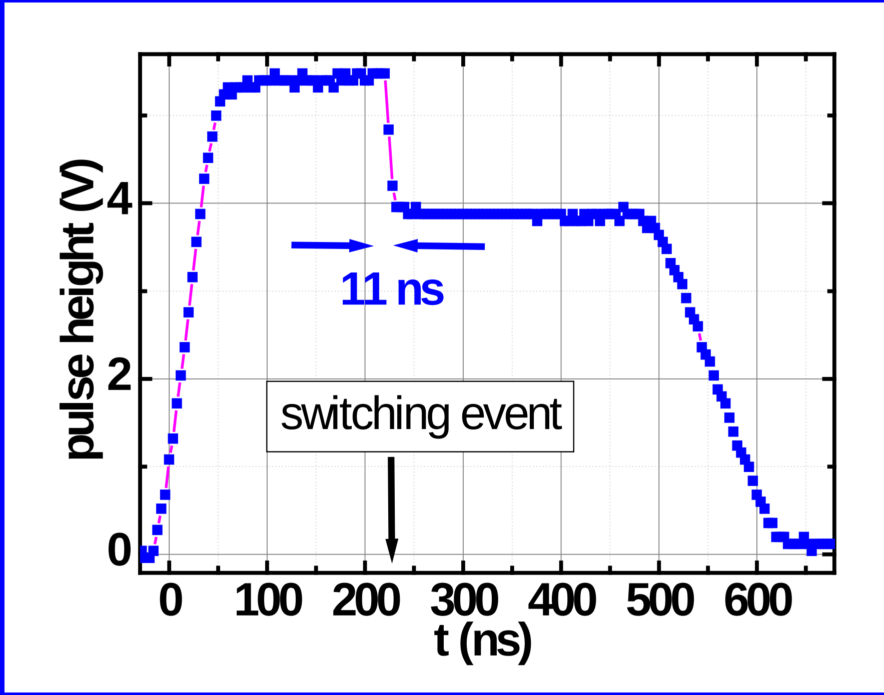


- **Quasi-static switching curves determine critical field**
- **Switching power is about 50µW with leakage currents.**
- **Very low power levels: 5 µA @ 1.5 V (P= 7.5 µW)**

F. Kreupl et al.

Ins. Carbon: Read Endurance & Speed

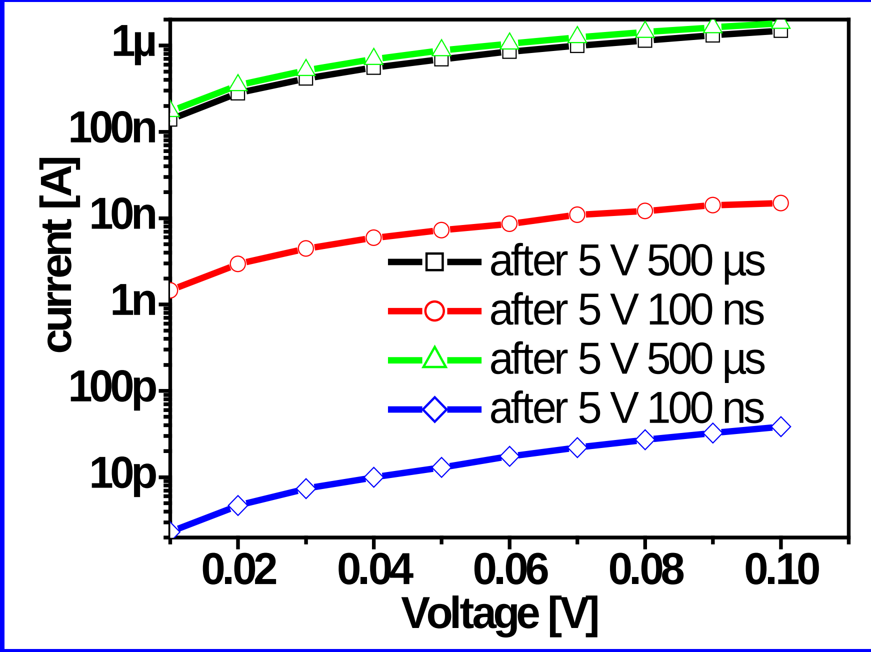


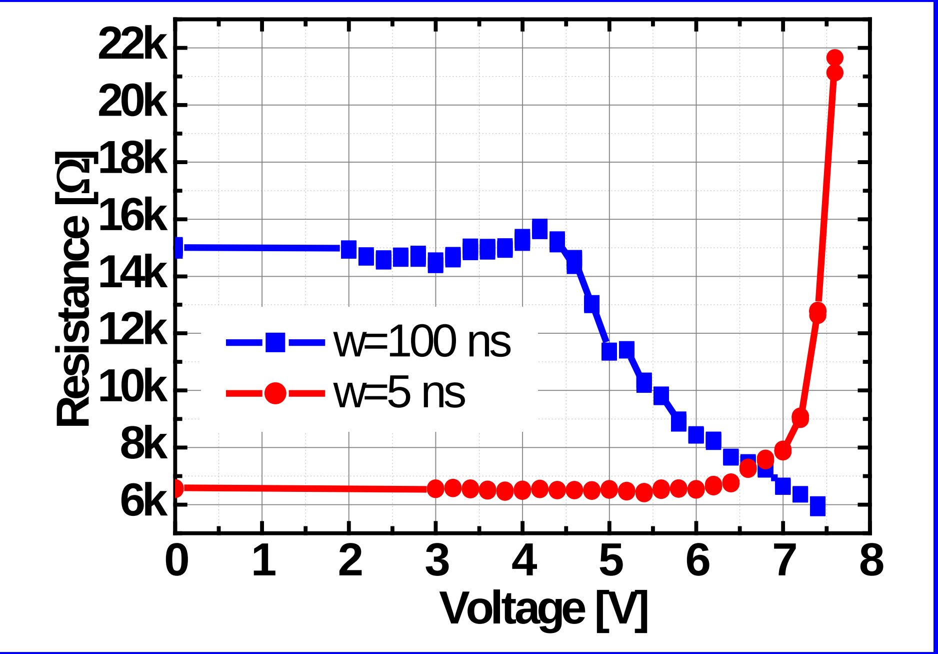


- **Read endurance at 75 degree C:**
  $2.3*10^{13}$ read cycles at 0.1 V.
- **Switching speed is faster than 11 ns.**

F. Kreupl et al.

Insulating Carbon: Switching

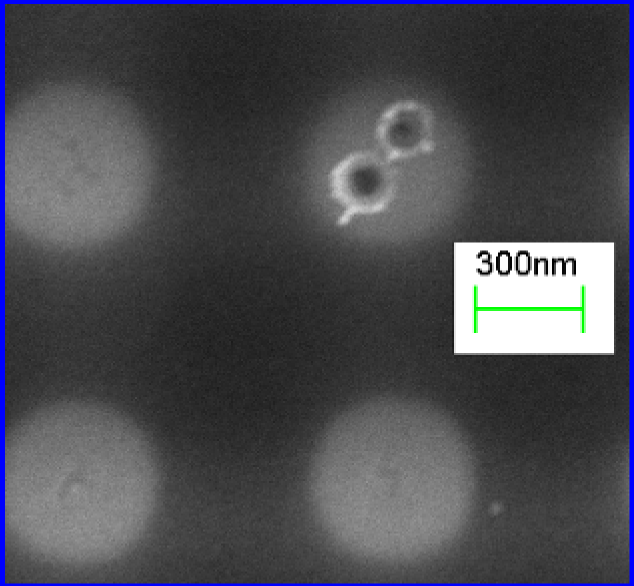


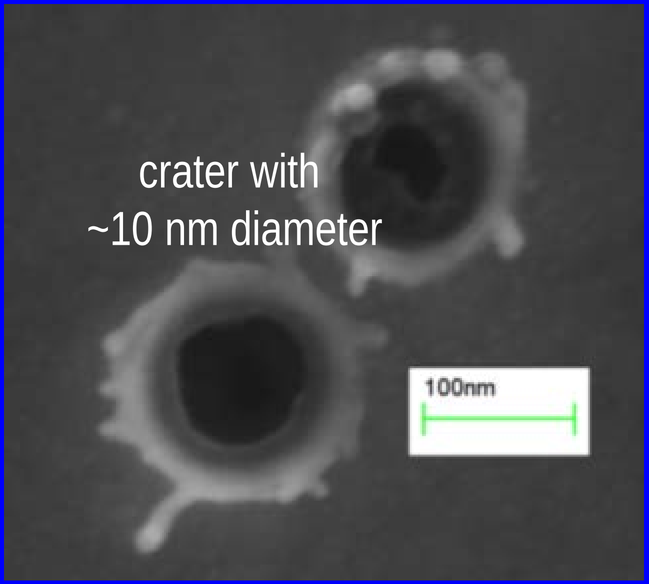


- **I(V) curves show similar behavior after pulses**
- **Resistance level can be trimmed by individual voltage pulses (multi-level capability)**

F. Kreupl et al.

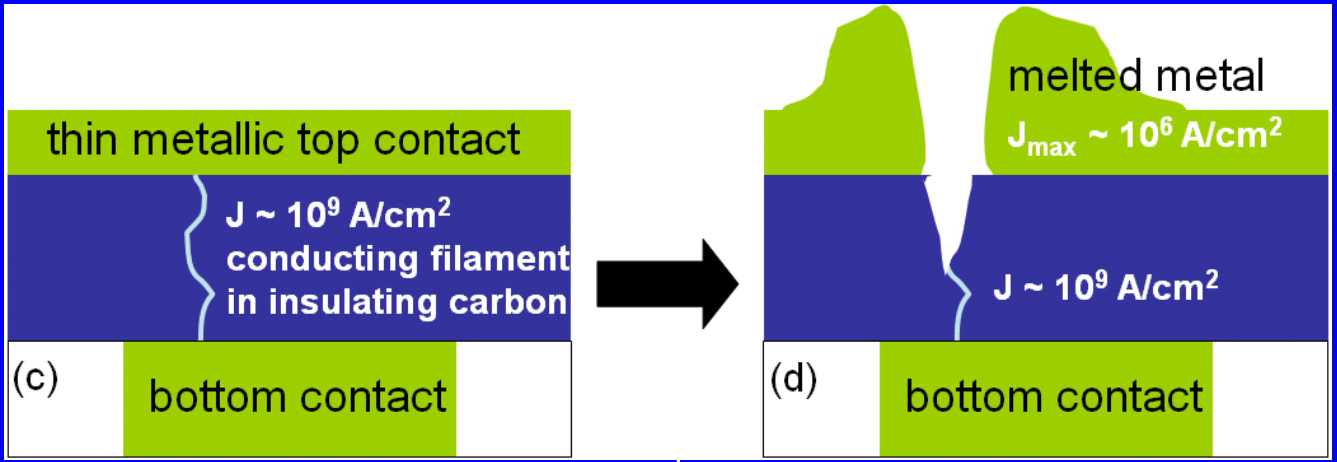
Insulating Carbon: Filament size





10 V pulse evaporates metal ➔ filament ~ 10 nm @ 10 V

➔ use carbon as current spreader



Conclusions

- New carbon memory proposed based on sp^2 to sp^3 conversion
- Inherently fast: reset ~ ns, set ~ ns
- Nanotubes need ~30 µA @ 8V
- Graphene-like Conductive Carbon needs pores < 6 nm
- Insulating Carbon shows lowest switching power: 5 µA @ 1.5 V (P= 7.5 µW)
- Pulses and cell design needs to be optimized
- Should also work with Fullerens, Graphene and Diamonds

Acknowledgement

Qimonda Fab Dresden

Roland Thewes,

Werner Pamler,

Walter Weber,

Uli Klostermann,

Klaus-Dieter Ufert,

Henning Riechert

Stanford University

Thank you!

Questions?