Chemical Vapor Deposition Processing of Diamond Films

Presenter:
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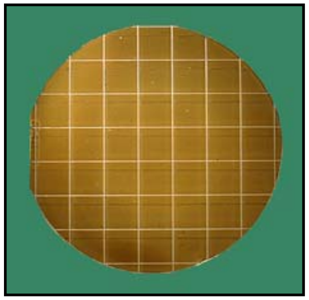
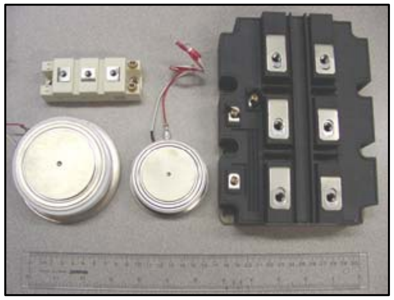
Annual DOE Peer Review Meeting - 2008
DOE Power Electronics Research Program
Washington, DC
30 September 2008

Research sponsored by the Electric Delivery Technologies Program, DOE Office of Electricity Delivery and Energy Reliability, under contract DE-AC05-00OR22725 with UT-Battelle, LLC.

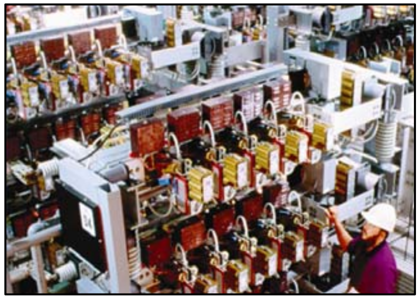
Research Needs for Power Electronics are Necessary at Many Levels



Applied Materials Research



Power Electronic Module Development



Next Generation Equipment

System Reliability

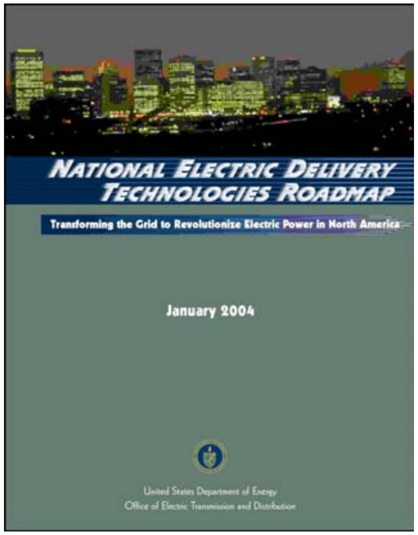
The work in this project addresses this area

Statement of the Problem

The need to "go beyond Si"

Development of new materials for power electronics building blocks and other grid components and systems will be one of the key activities for gaining:
-higher voltage (>10kV)
-higher current (>100A)
-higher frequency (>1kHz), and
-higher temperature (>250C)
operation.

These requirements can be met only by wide band gap semiconductors

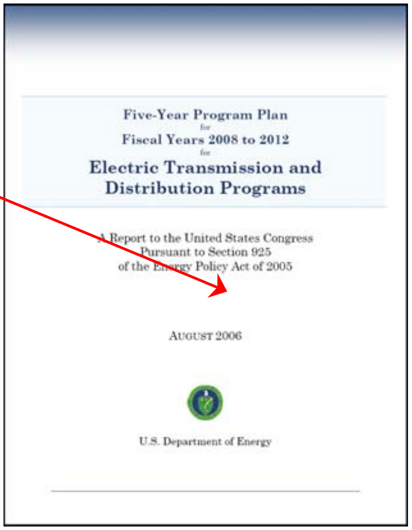


NATIONAL ELECTRIC DELIVERY TECHNOLOGIES ROADMAP

Transforming the Grid to Revolutionize Electric Power in North America

January 2004

United States Department of Energy
Office of Electric Transmission and Distribution

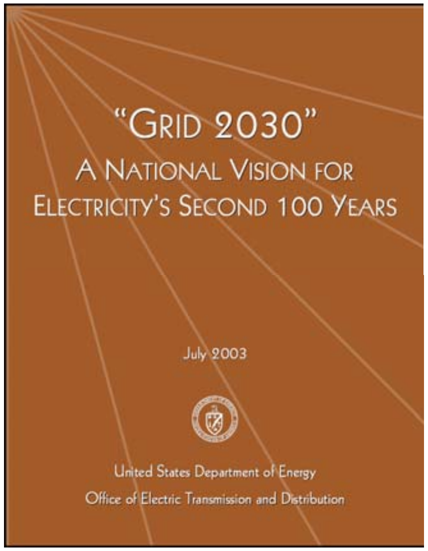


Five-Year Program Plan
for
Fiscal Years 2008 to 2012
for
Electric Transmission and Distribution Programs

A Report to the United States Congress
Pursuant to Section 925
of the Energy Policy Act of 2005

AUGUST 2006

U.S. Department of Energy



"GRID 2030"
A NATIONAL VISION FOR ELECTRICITY'S SECOND 100 YEARS

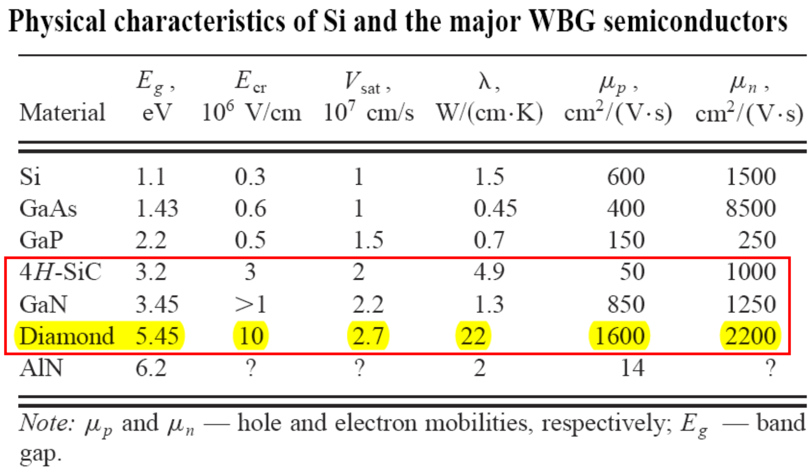
July 2003

United States Department of Energy
Office of Electric Transmission and Distribution

Why Diamond?

The various figure of merit values for diamond are up to 50 times higher than for any other semiconductor

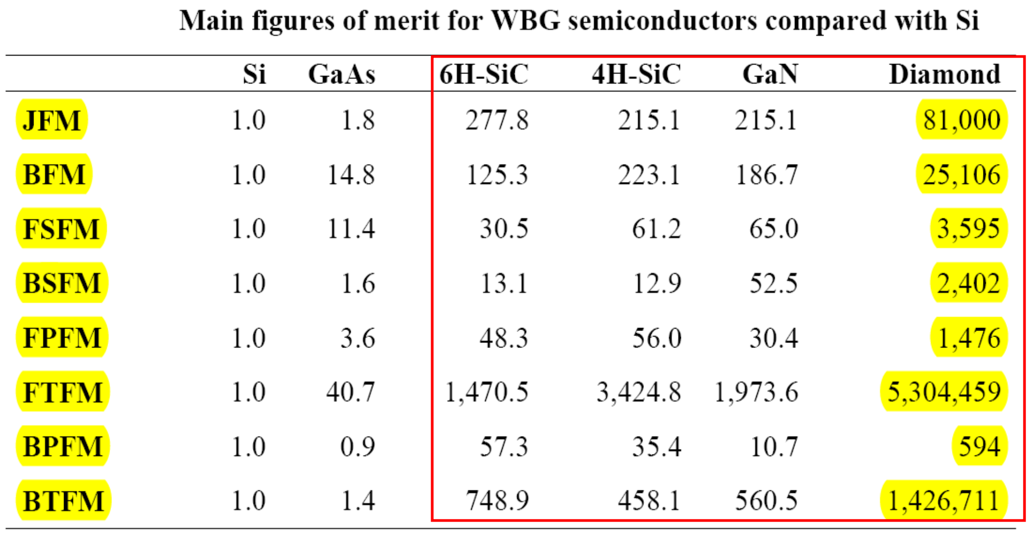
It has been demonstrated that CVD diamond can switch 100 kW of power at MHz frequencies, (R.D. Scarpetti et al. Ninth-IEEE-International Pulsed Power Conference, 2, 813 (1993).



Physical characteristics of Si and the major WBG semiconductors

Material	E_g, eV	E_{cr}, 10^6 V/cm	V_{sat}, 10^7 cm/s	λ, W/(cm·K)	μ_p, $cm^2/(V \cdot s)$	μ_n, $cm^2/(V \cdot s)$
Si	1.1	0.3	1	1.5	600	1500
GaAs	1.43	0.6	1	0.45	400	8500
GaP	2.2	0.5	1.5	0.7	150	250
4*H*-SiC	3.2	3	2	4.9	50	1000
GaN	3.45	>1	2.2	1.3	850	1250
Diamond	5.45	10	2.7	22	1600	2200
AlN	6.2	?	?	2	14	?

Note: μ_p and μ_n — hole and electron mobilities, respectively; E_g — band gap.



Main figures of merit for WBG semiconductors compared with Si

	Si	GaAs	6H-SiC	4H-SiC	GaN	Diamond
JFM	1.0	1.8	277.8	215.1	215.1	81,000
BFM	1.0	14.8	125.3	223.1	186.7	25,106
FSFM	1.0	11.4	30.5	61.2	65.0	3,595
BSFM	1.0	1.6	13.1	12.9	52.5	2,402
FPFM	1.0	3.6	48.3	56.0	30.4	1,476
FTFM	1.0	40.7	1,470.5	3,424.8	1,973.6	5,304,459
BPFM	1.0	0.9	57.3	35.4	10.7	594
BTFM	1.0	1.4	748.9	458.1	560.5	1,426,711

SiC and GaN are only transition materials, diamond is the material of the future for power electronics

What are the Challenges in Diamond Growth?

1) Lack of diamond wafers

2) Low film growth rates

These challenges are addressed by the following two ORNL projects

1) A new film growth method for diamond CVD

2) Novel, flexible, low-cost large-area diamond substrates

Project 1:

High Flux Molecular Jet CVD for Rapid Diamond Growth

Gyula Eres, H.M. Christen

Start date June 2008

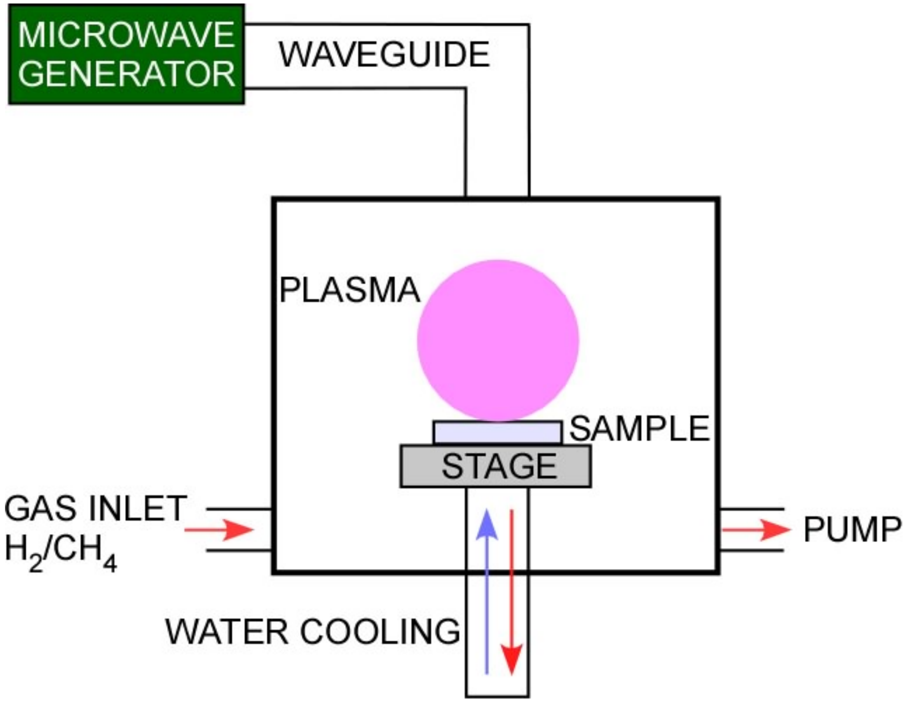
State-of-the-Art in Diamond CVD

Microwave Plasma Enhanced CVD of Diamond

Recently homoepitaxial (diamond on diamond) growth rates of 150 μ/h have been demonstrated

Homoepitaxy is not an option because diamond substrates are too small and too expensive

Heteroepitaxial (diamond on foreign substrates) growth rates are still much lower, roughly 1 μ/h



The large discrepancy between homo- and heteroepitaxial growth rates indicates that solving the problem of heteroepitaxial growth requires a look at different growth method

High Flux Molecular Jets for Fast Diamond CVD

ADVANTAGES OVER MW PLASMA CVD

SCALE UP

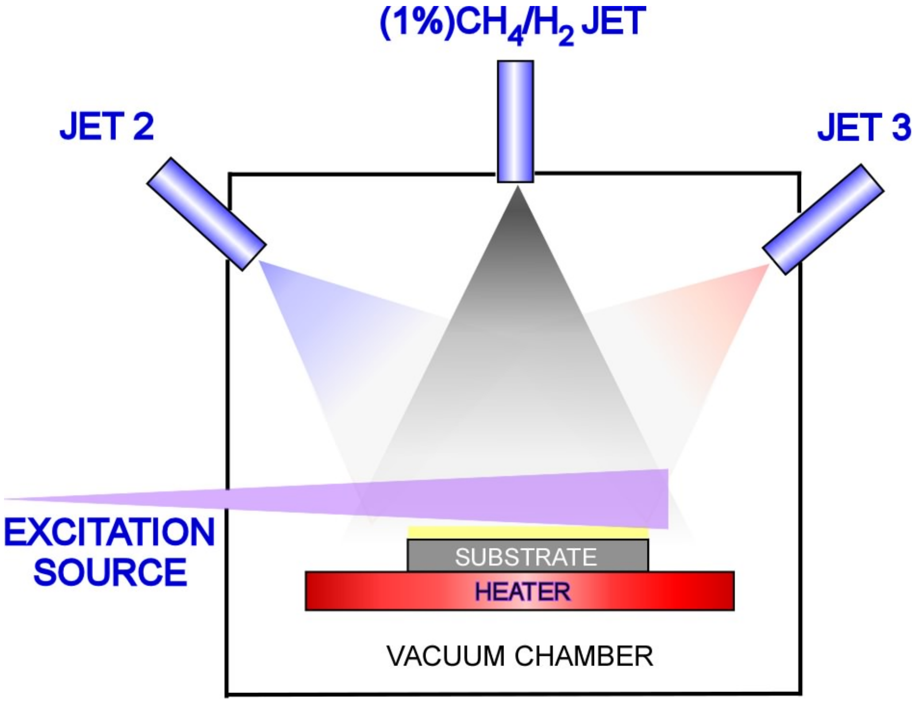
Flux of the growth species is limited only by the available pumping speed

VERSATILITY

Multiple independently controllable sources for growth and doping

CONTROL

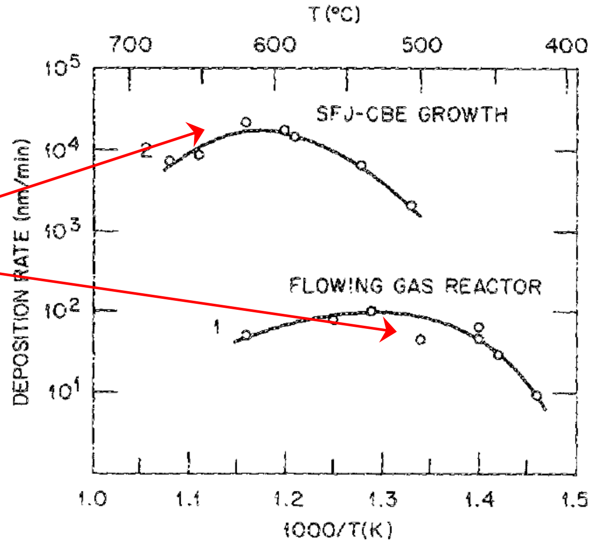
High flux is used to control both, the growth mode and the growth rate



Previous Results with Molecular Jet CVD at ORNL

FAST GROWTH

Two orders of magnitude increase in heteroepitaxial growth of Ge on GaAs and Si(100) at rates > 10 μ/min,
APL 55, 1008 (1989)

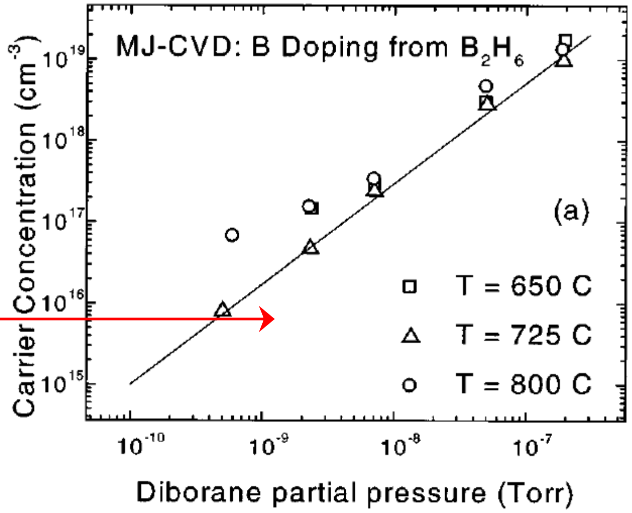


WIDE BANDGAP MATERIAL GROWTH

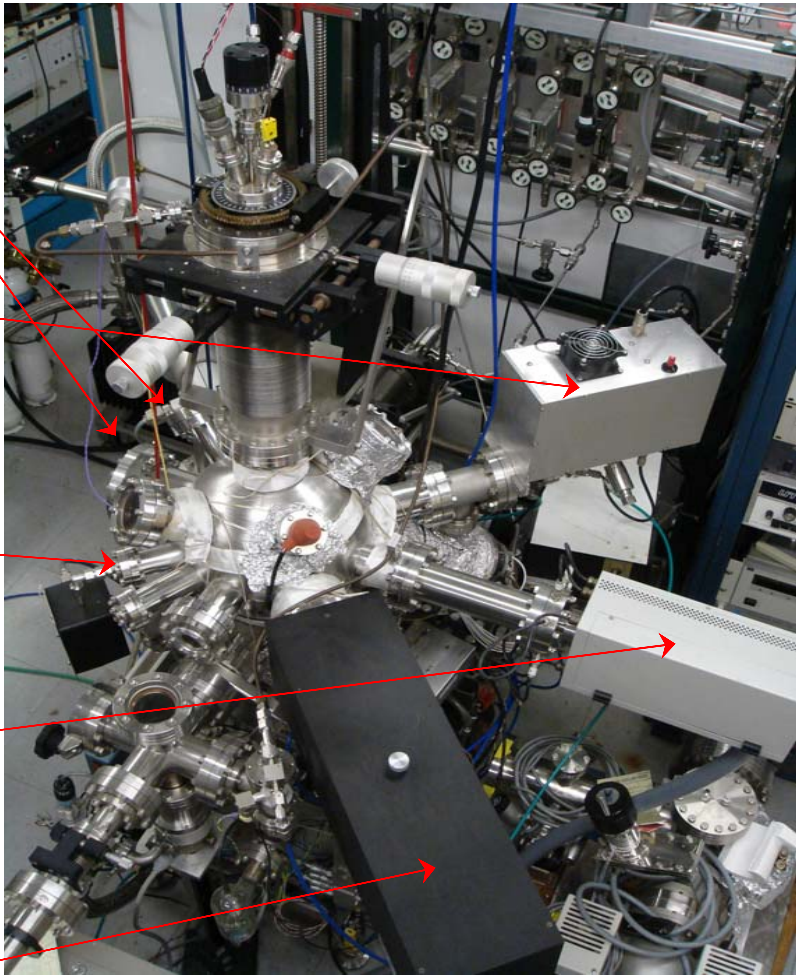
Heteroepitaxial growth of SiC on Si(100)
Proc. Sixth Intern. Conf. on Silicon Carbide and Related Materials (ICSCRM), 1995

DOPING AND DEVICE FABRICATION

Growth and doping for solar cell device fabrication has been demonstrated
APL 71, 2812 (1997)



Molecular Jet Growth System



Multiple Jet Sources

Atomic Beam Generation Source

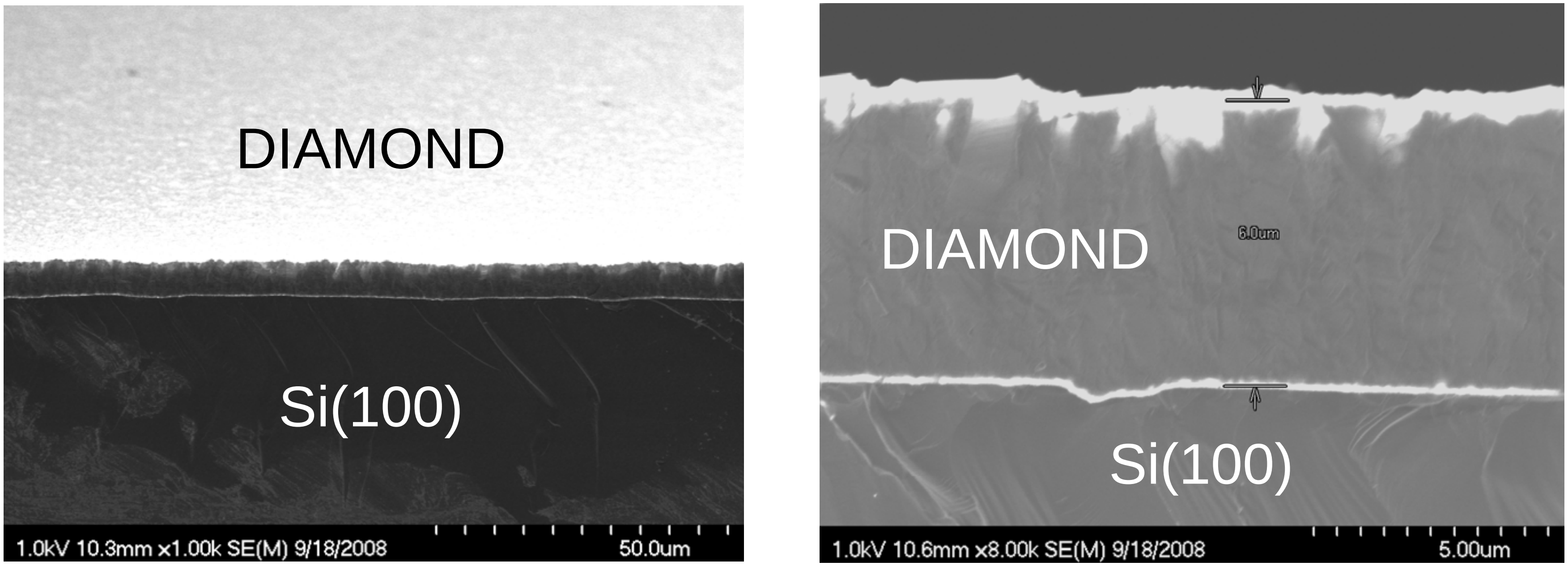
Optical Reflectivity

Quadrupole Mass Spectrometer

RHEED System

ORNL CVD Diamond Films

SEM images of diamond films on Si(100)



Preliminary results illustrating that high growth rates that ensure continuous diamond film growth on Si have been achieved

Summary of Milestones and Accomplishments

(Project 1)

MILESTONES

Set up a molecular jet growth system for fast CVD growth of diamond

Reach growth rates that ensure continuous film growth on non-diamond materials. This is important for the growth of smooth high quality films

ACCOMPLISHMENTS

The molecular jet growth systems has been optimized for diamond film growth

Continuous diamond films have been grown on Si(100) surface at high rates

Project 2:

Novel, Flexible, Large-Area, Low-Cost Substrates for Diamond Growth

A. Goyal, L. Heatherly, L. Wilson

Fabrication of large Area, Flexible, Heteroepitaxial, Single-crystal-like Diamond Films on Low Cost Substrates

Technical Issues

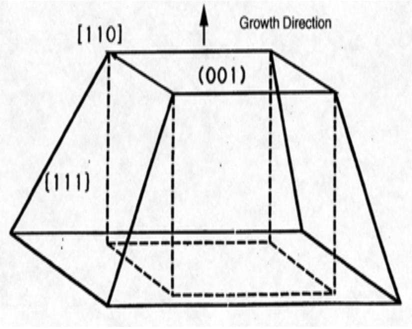
- On most substrates, only non-epitaxial growth occurs resulting in polycrystalline films.
- For several decades, epitaxial diamond films could only be grown homoepitaxially on diamond substrates
- *Very high growth stresses* were encountered in the polycrystalline films, further reducing the choice of substrates
- It was not possible to create n-type doping of diamond, hence device fabrication was not possible

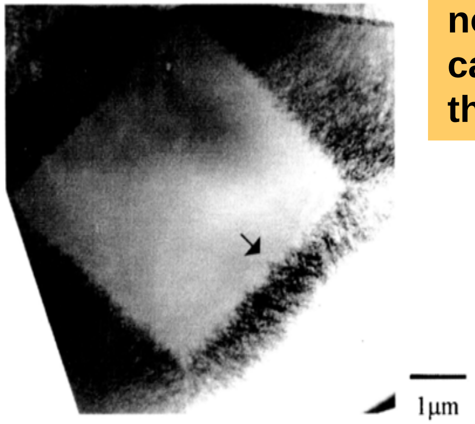
Recent Advances which make diamond-based electronics promising

- ➢ Heteroepitaxial growth of diamond has been recently demonstrated on Iridium surfaces.
- ➢ Thick epitaxial diamond films on Ir-coated single crystals such as Ir/$SrTiO_3$; Ir/MgO; Ir/Al_2O_3 have been demonstrated
- ➢ It has also been recently demonstrated that both n-type and p-type doping of diamond is possible
- ➢ What is lacking is a large-area, low-cost substrate for enabling all the potential applications

Smooth, crack-free, heterepitaxial diamond films have recently been grown on single-crystal Ir (100) using bias-enhanced nucleation

The problem of high, intrinsic growth stresses in diamond films was solved by BEN & epitaxial growth along [001]





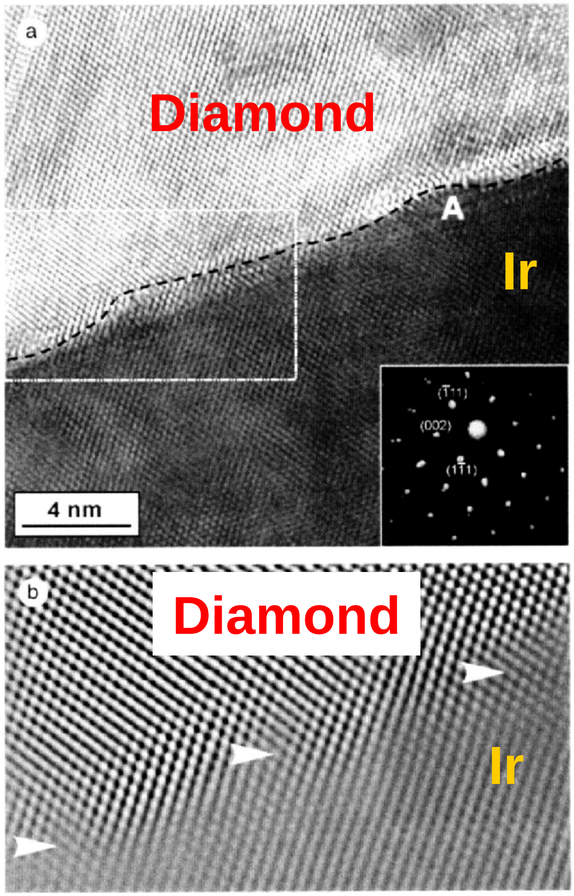
High stresses due to highly defective regions associated with incorporation of non-diamond carbon content in the film

Diamond (100)

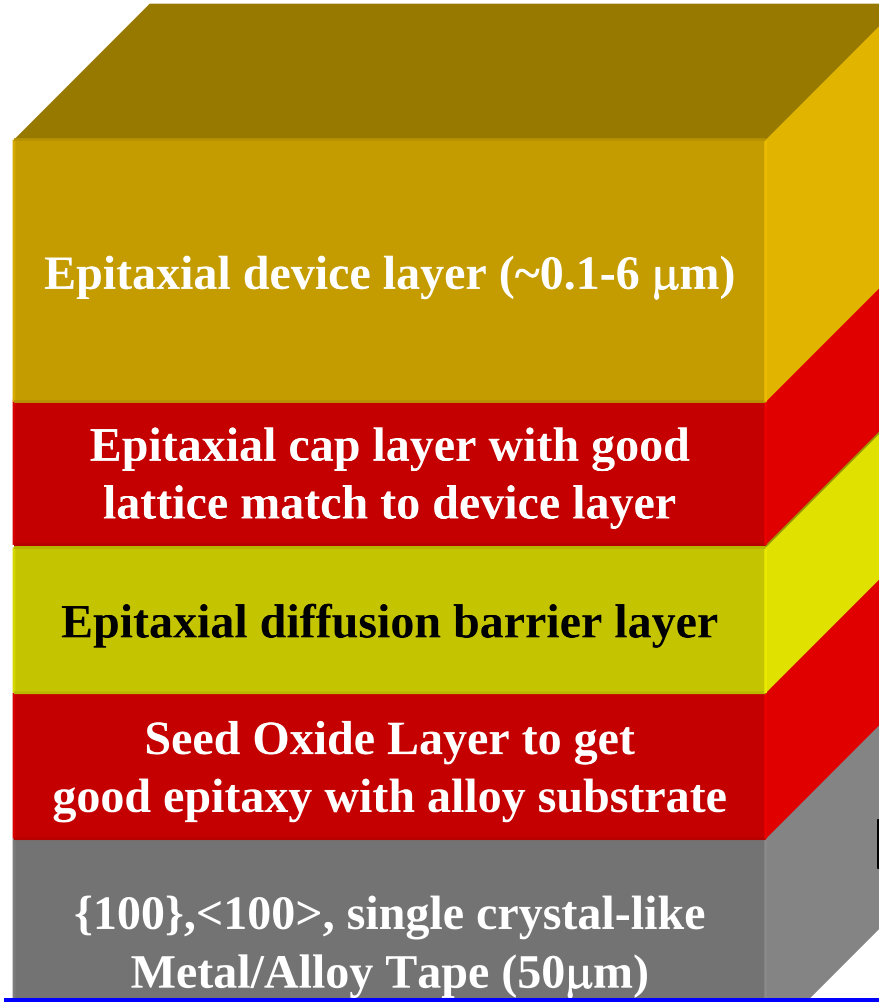
Iridium

$SrTiO_3$ (100) Single crystal

Ando, et. al., Hormann et al.



Large-area, flexible, single-crystal-like devices can be fabricated on {100}<100> textured, single-crystal-like metal/alloy tapes



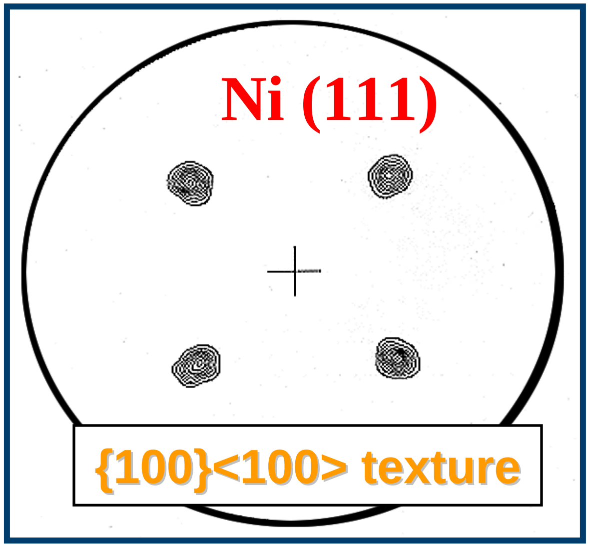
Epitaxial device layer (~0.1-6 μm)

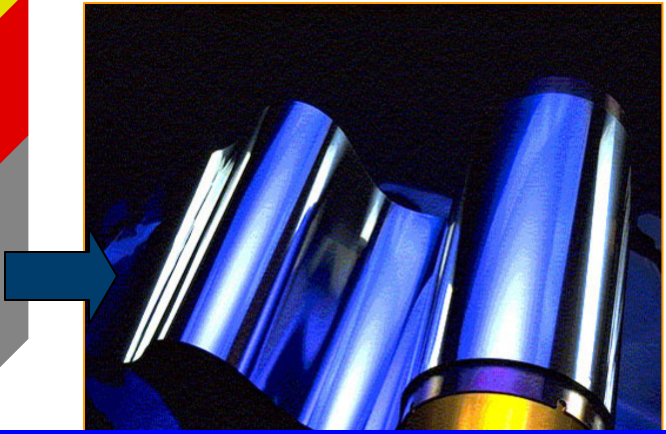
Epitaxial cap layer with good lattice match to device layer

Epitaxial diffusion barrier layer

Seed Oxide Layer to get good epitaxy with alloy substrate

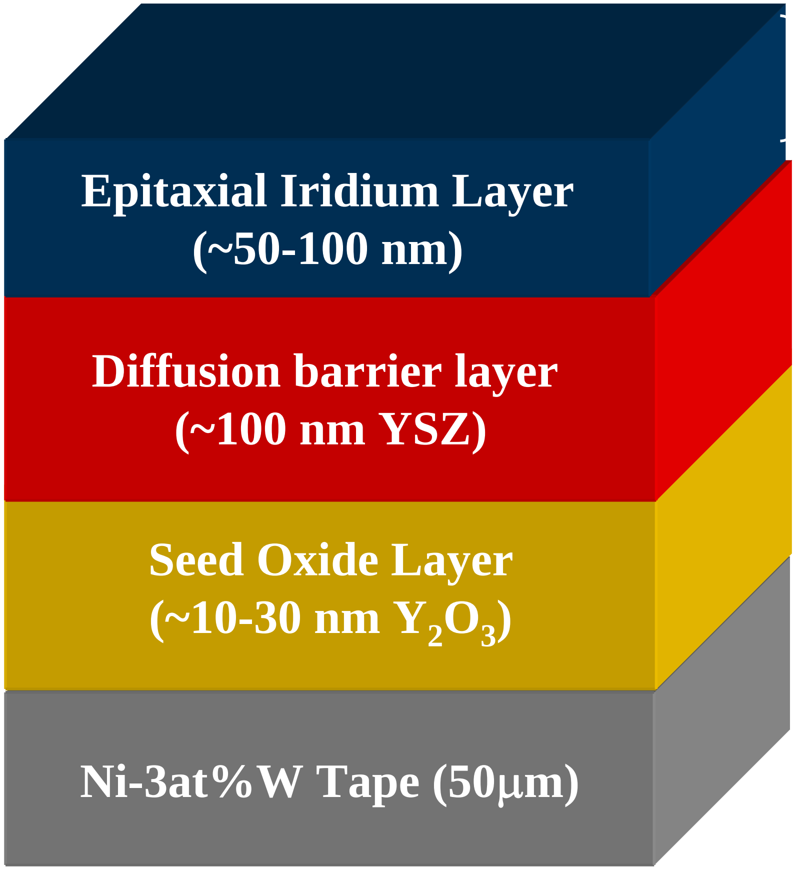
{100},<100>, single crystal-like Metal/Alloy Tape (50μm)





Process already being used to fabricate hundreds of meters of low-cost, single-crystal-like, high temperature superconducting wires with a price/performance better than that for copper wire!

Single-crystal-like, multilayer, large-area, flexible substrates have been fabricated for growth of diamond films

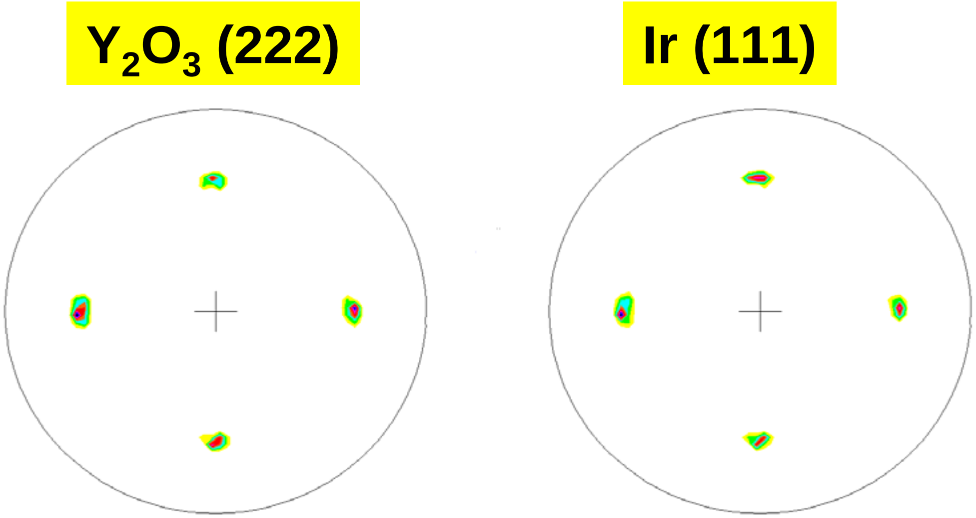


Epitaxial Iridium Layer (~50-100 nm)

Diffusion barrier layer (~100 nm YSZ)

Seed Oxide Layer (~10-30 nm Y_2O_3)

Ni-3at%W Tape (50µm)

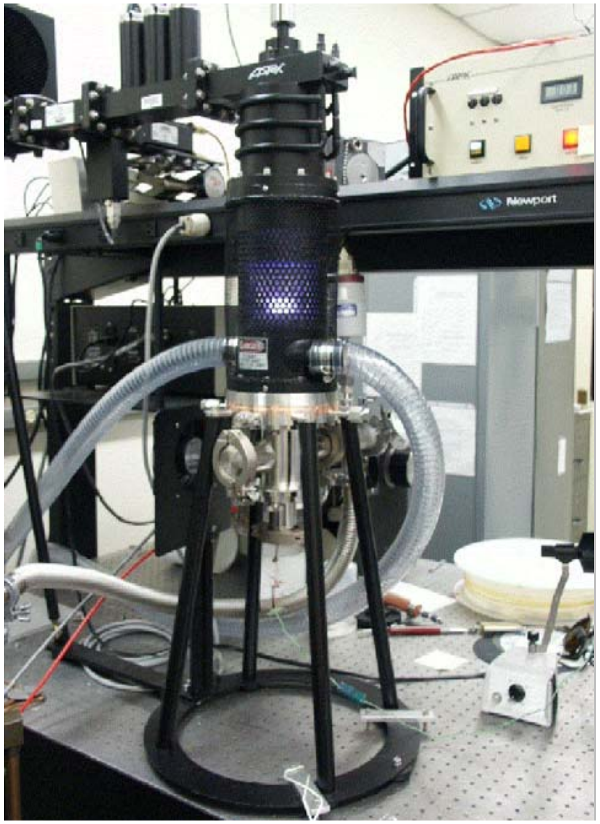


100% rotated cube-on-cube epitaxy on Ni-3at%W {100}<100< substrates

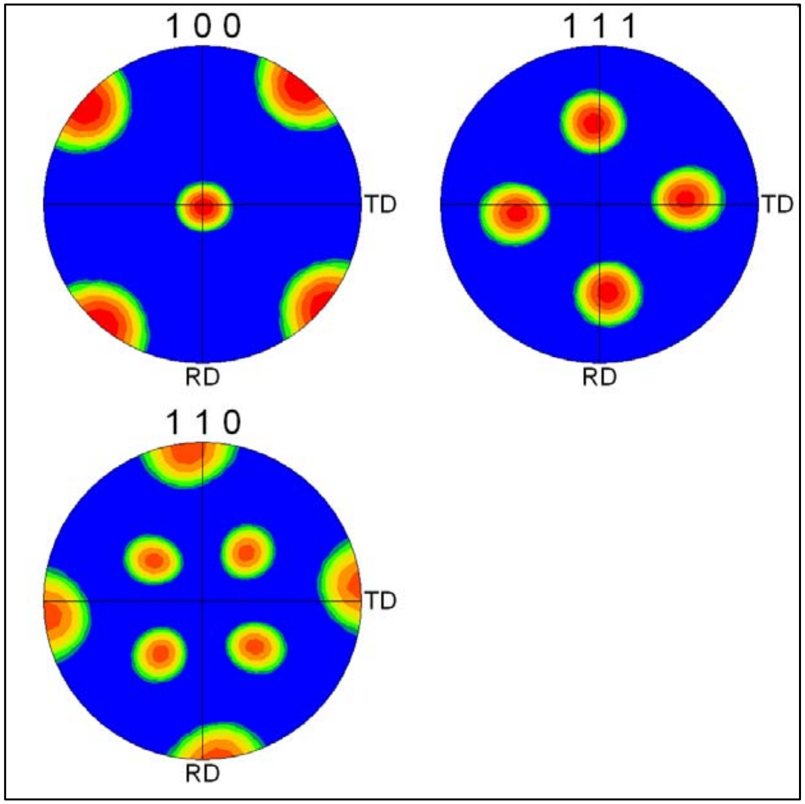
For single crystal Ir/$SrTiO_3$, the Ir(111) pole figure would also have four points, with each point a little less wide.

Microwave plasma-enhanced CVD process was used to grow heteroepitaxial diamond films on these single-crystal-like substrates

Diamond forms from an activated mixture of hydrocarbon gases and hydrogen



Electron backscatter Kikuchi diffraction data from diamond film shows a 45°-rotated, heteroepitaxial, diamond film



Summary of Milestones and Accomplishments
(Project 2)

Milestones:

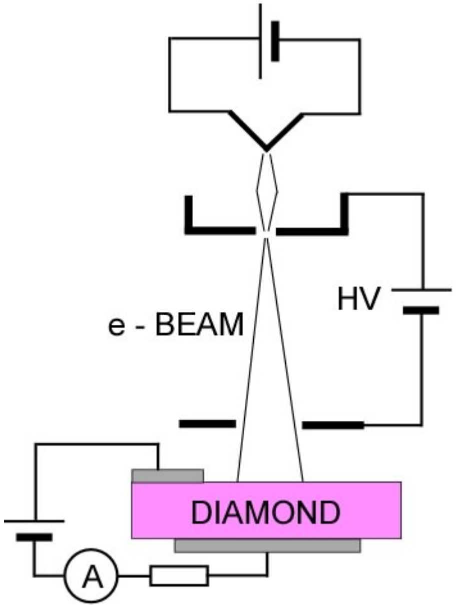
1. Demonstrate feasibility of large area, flexible, non-diamond substrates with surfaces compatible for diamond growth
(Due Sept. 30, 2008 – completed)

2. Demonstrate nucleation & growth of single-orientation, epitaxial diamond films on such substrates demonstrated
(Due Sept. 30, 2008 – completed)

Major Accomplishment:

First demonstration of a large-area, flexible, non-diamond substrate for diamond-based devices

Future Tasks



Project 1:

1) Optimize molecular jet diamond film quality in fast heteroepitaxial growth

2) Develop n- and p-type doping methods for molecular jet diamond CVD films

3) Construct an e-beam switch for testing diamond film quality and optimize it for high power switching

Project 2:

1) Find optimal conditions for bias-enhanced nucleation which is a critical step to obtain heteroepitaxy of diamond on Ir surfaces using PECVD

2) Find optimal conditions for growth of epitaxial, [100] oriented, thick diamond films to result in low defect densities