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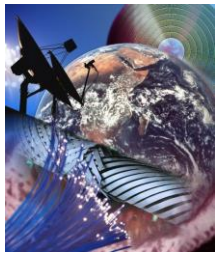

Beyond Silicon…

Advanced Power Electronics for FACTS Technology

Jerry Melcher

APE Initiative Lead

Energy Delivery and Utilization

EPRI

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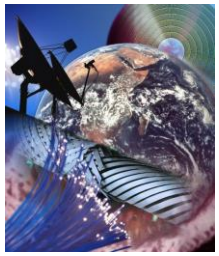


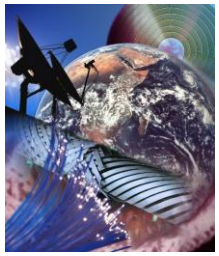
Initiative Objectives

- Why are we doing this?

- Where are we going?

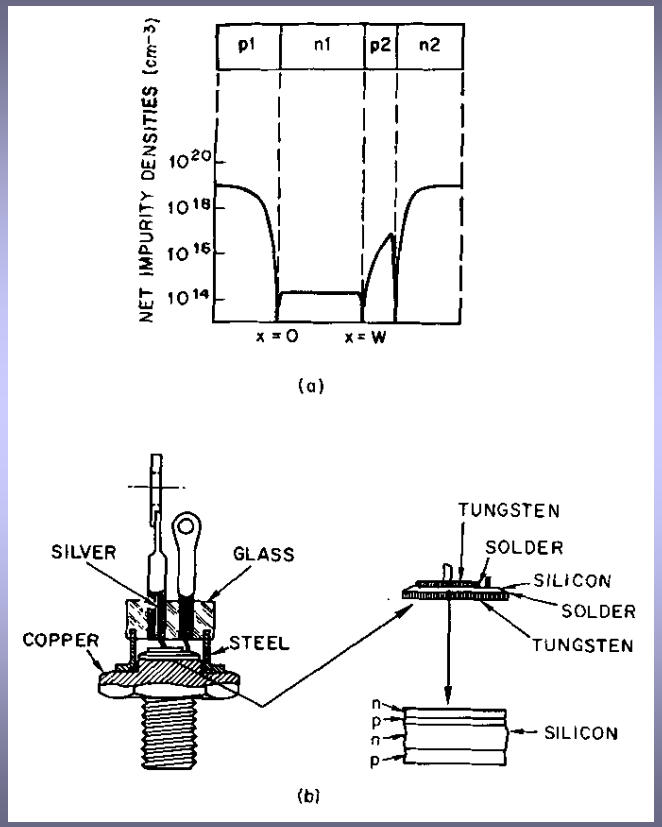
Strategic S&T

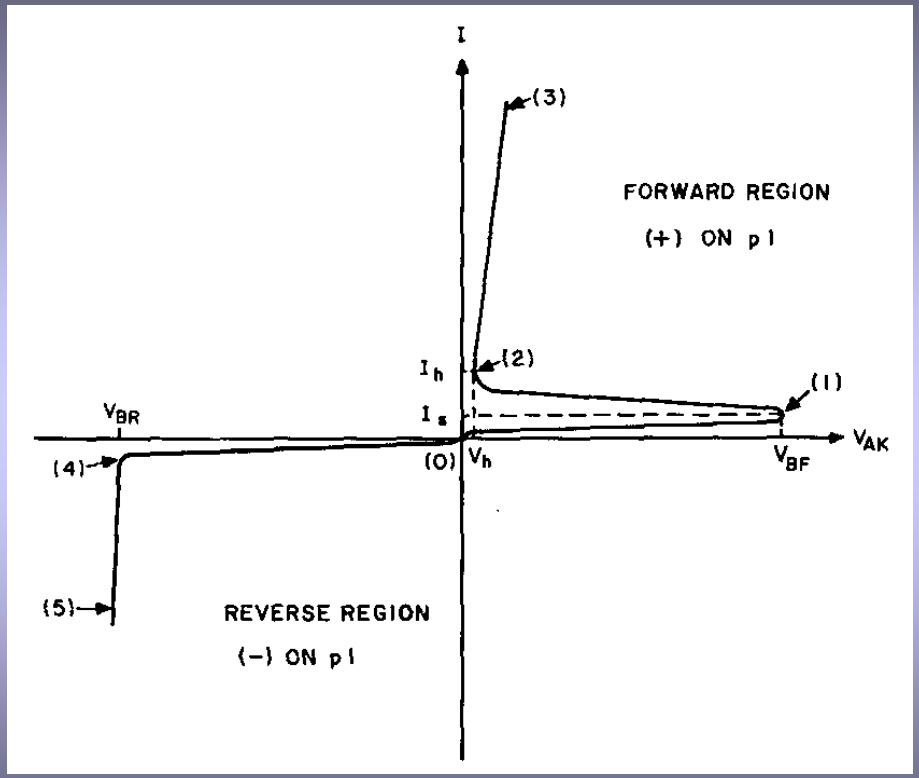
Strategic Initiative Program



Power Electronics

The Thyristor





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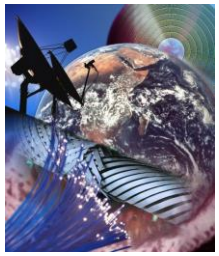
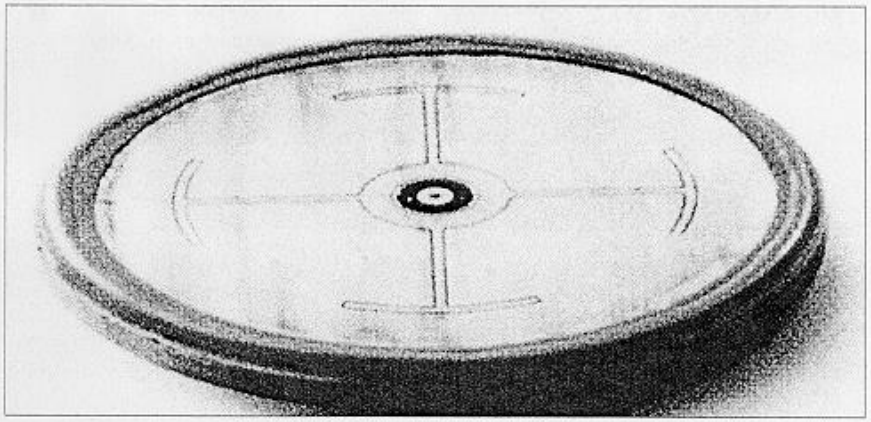
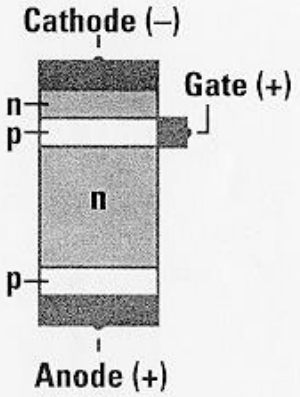


Thyristor - SCR

Semiconductor-Controlled Rectifier (SCR)





Advantage: solid state power control

Disadvantage: once turned on, an SCR continues to conduct regardless of voltage

Usage Boundaries: <6000 V, 2000–4000 A

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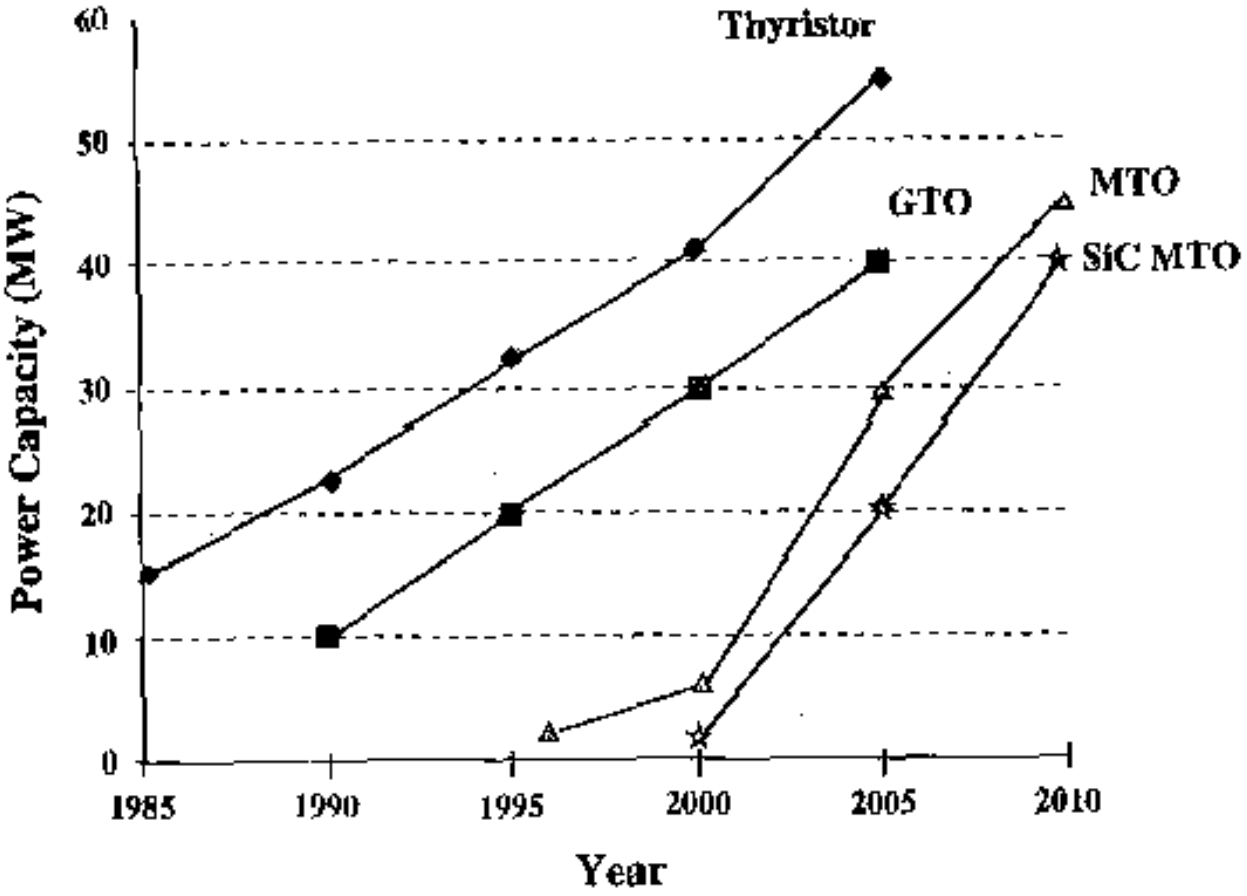
Power Progress for Si



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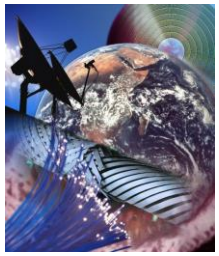

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  - *Si Power Devices are Reaching Their Fundamental Limits of Performance.*
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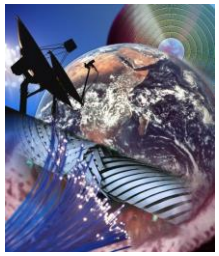
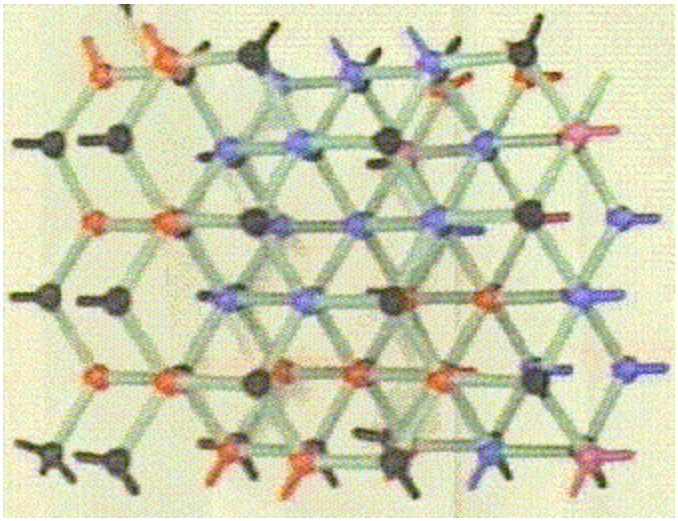
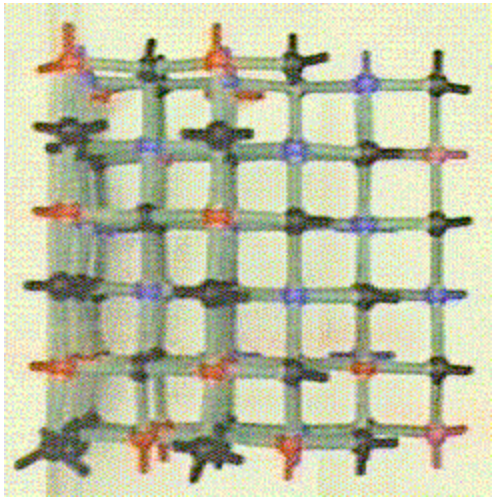
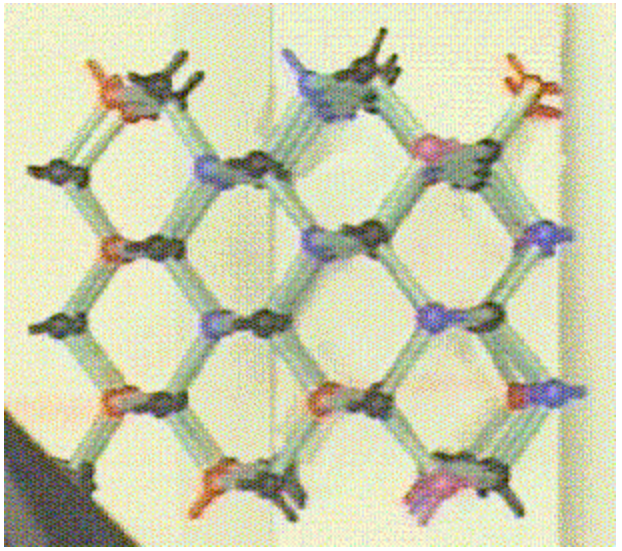


The "Diamond" Structure







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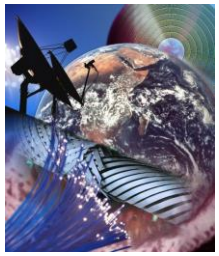
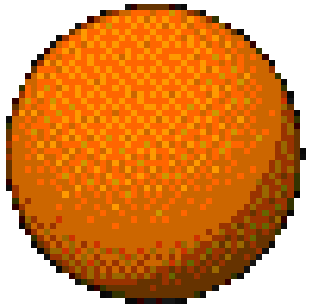
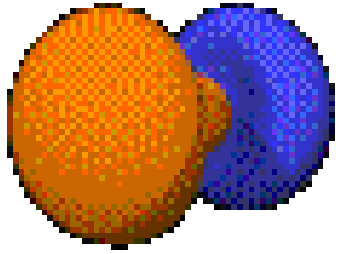


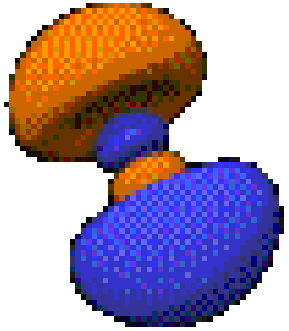
Si Electrons

3s



3p





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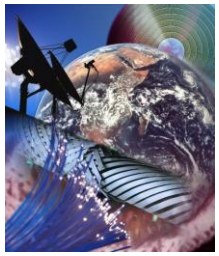
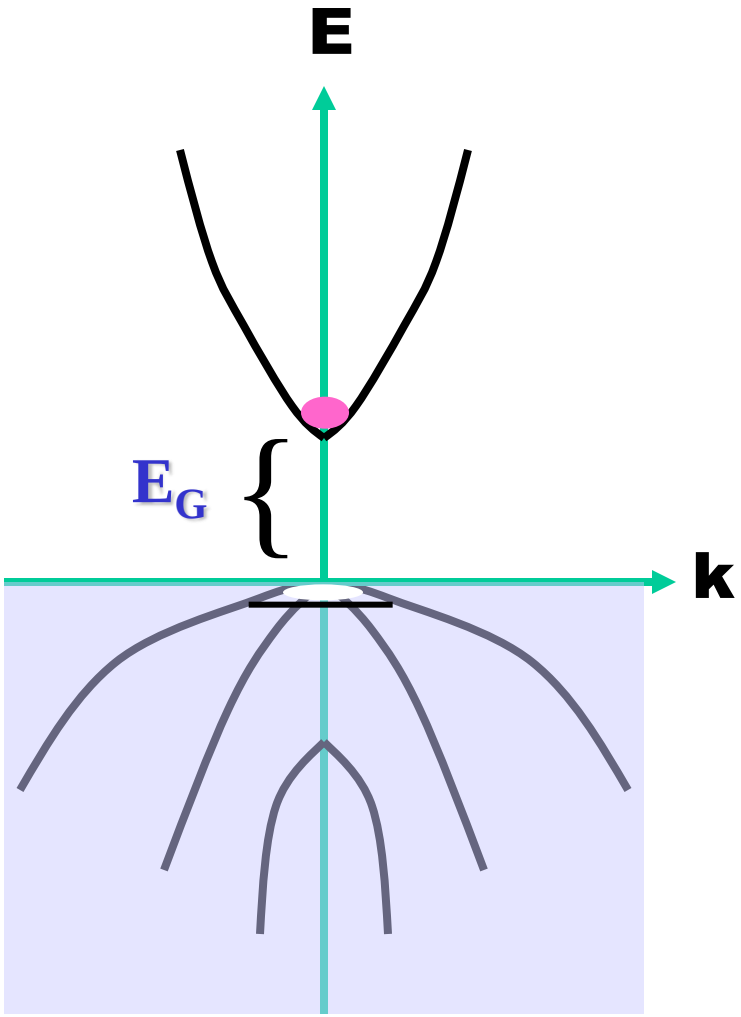


Physics of Semiconductors



k•p Perturbation Theory

$$\varepsilon_n(\mathbf{k}) = \varepsilon_n(0) + \frac{\hbar^2 k^2}{2m} + \frac{\hbar^2}{m^2}\sum_{j\neq n}\frac{\left|\langle n0|\mathbf{k}\bullet\mathbf{p}|j0\rangle\right|^2}{\varepsilon_n(0)-\varepsilon_j(0)},$$

$$\frac{m}{m^*} = 1 + \frac{2}{m}\sum_{j\neq n}\frac{\left|\langle n0|\mathbf{pp}|j0\rangle\right|}{\varepsilon_n(0)-\varepsilon_j(0)},$$

$$\frac{m}{m^*} \approx \frac{2}{mE_G}\sum_{v}\left|\langle c|\mathbf{pp}|v\rangle\right|$$

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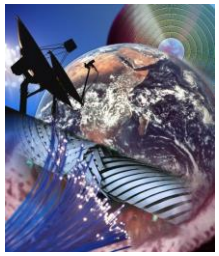

Chemistry of Semiconductors

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Unq	Unp	Unh	Uns	Uno	Une	Uun	Uuu	Uub						
		La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	
		Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr	

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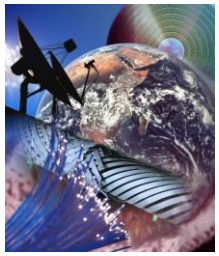

Initiative Objectives

- Why are we doing this?
  - *Si Power Devices are Reaching Their Fundamental Limits of Performance.*
- Where are we going?
  - ***SiC and GaN have Breakdown Electrical Fields ~10 Times Higher than Si. Both 4 Times the Forward Current…at the Same Unit Cost!*** ***(maybe)***

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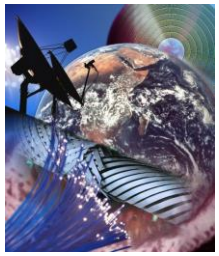

EPRI/DARPA

13-18 M$, 3 Years

• Nasa-Lewis	SiC
• Northrup-Grumman	SiC
• Vanderbilt University	SiC
• Silicon Power Corp	SiC
• University of Florida	GaN
• Cal Tech	GaN

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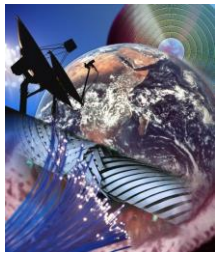

Advantages of Post-Silicon Materials

Property	Si	3C SiC (6C SiC)	CVD Diamond	GaN	Importance
Bandgap (300K) Voltage	*1.1*	*2.2 (2.9)*	*5.5*	*3.4*	*Blocking*
Maximum Operating Power Flow Temp (K)	*500*	*>900 (>1000)*	*1400*	*>800*	*Limits*
Breakdown Voltage (Eb, 10^6 V/cm)	*0.3*	*4*	*10*	*5*	*Maximum Power Capacity*
Hole Mobility Switching Speed (RT, cm^2/Vs)	*600*	*40*	*1600*	*200*	
Thermal Conductivity Rate (C_p, w/cm)	*1.5*	*5*	*20*	*1.3*	*Cooling*

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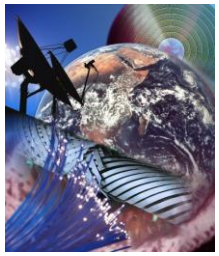
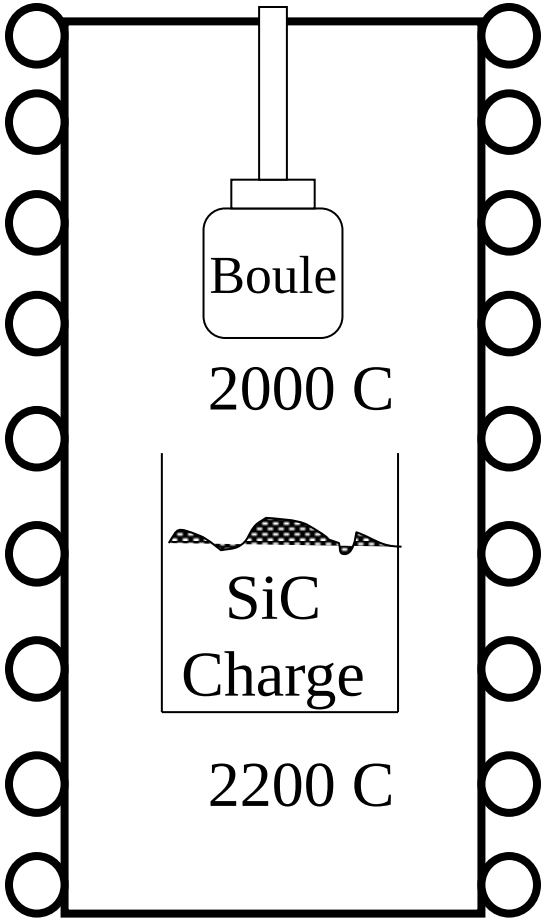
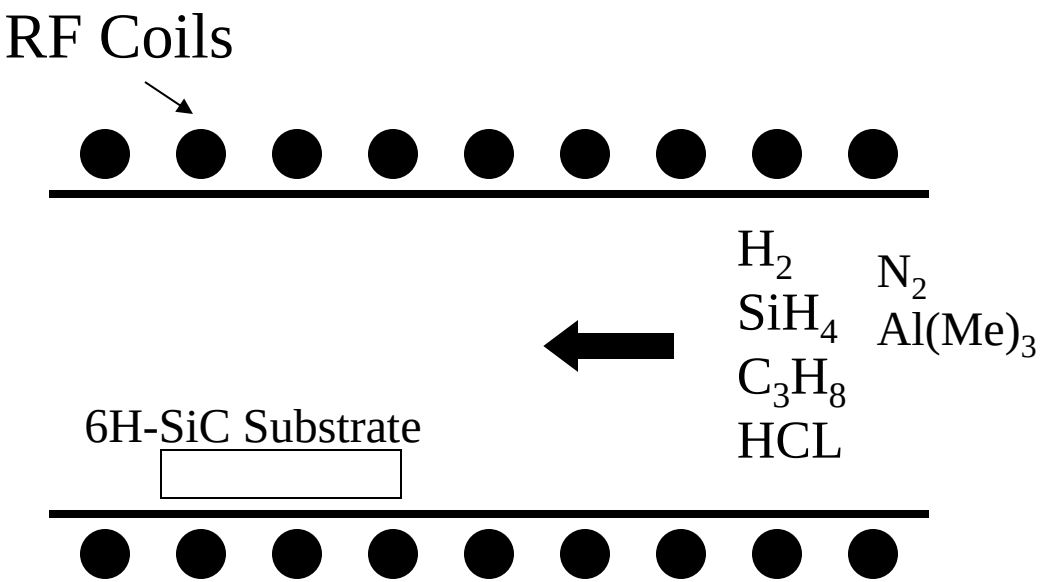


SiC Growth



Sublimation



CVD

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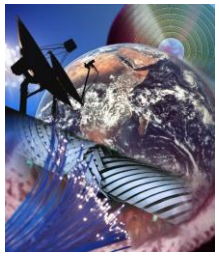
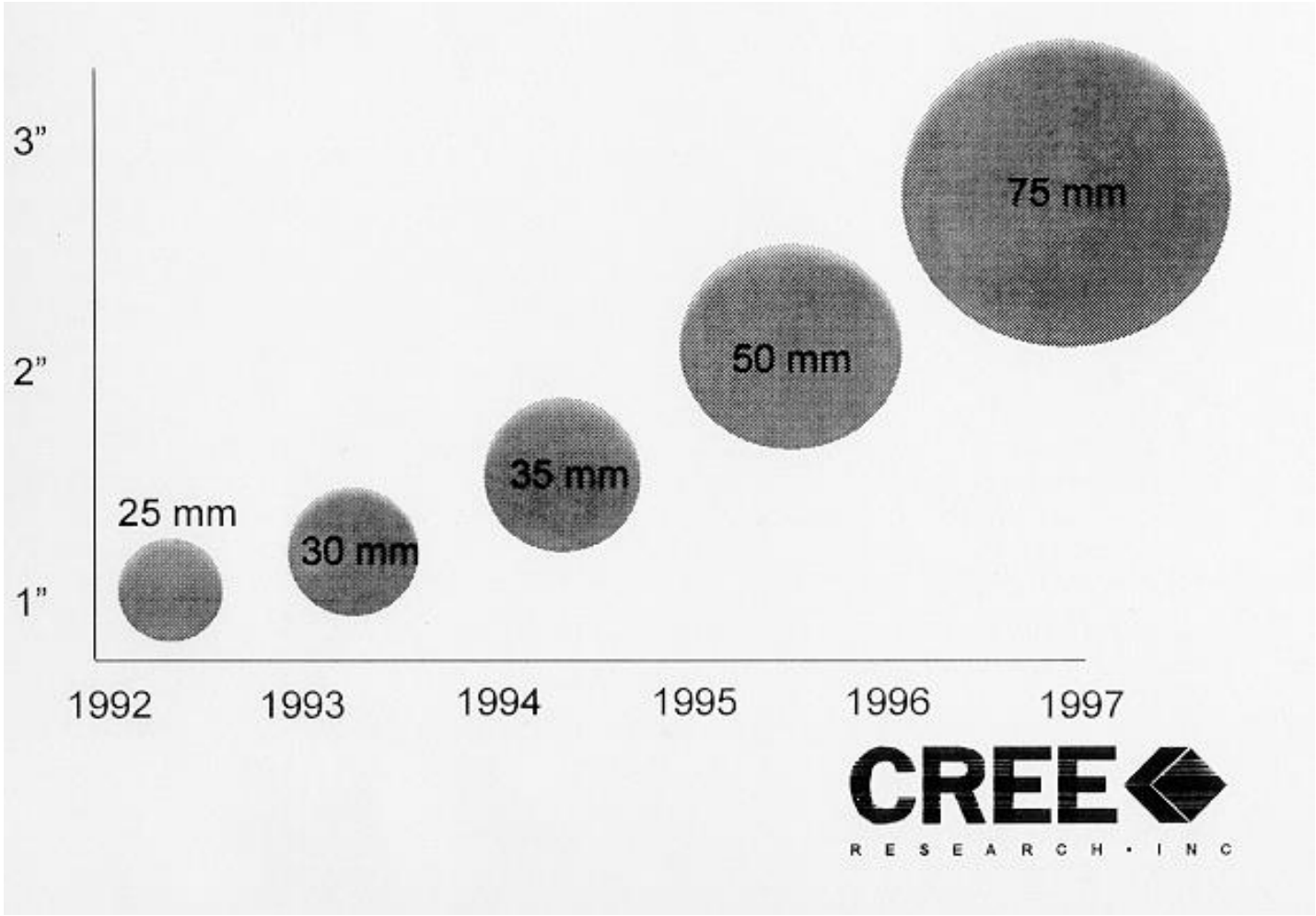


SiC: Progress in Wafer Size



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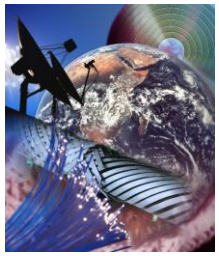
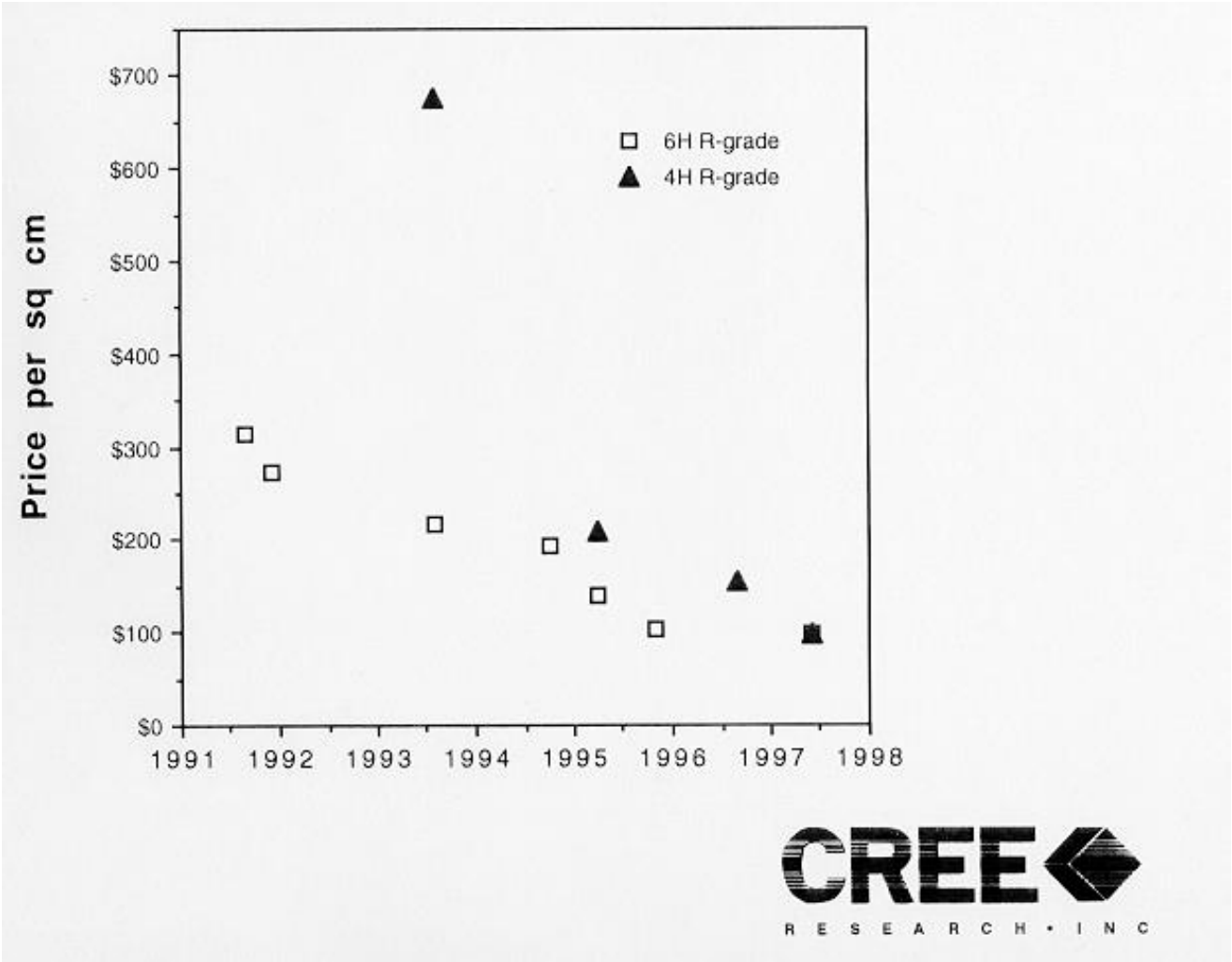


SiC: Wafer Price vs. Year



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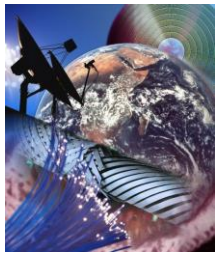
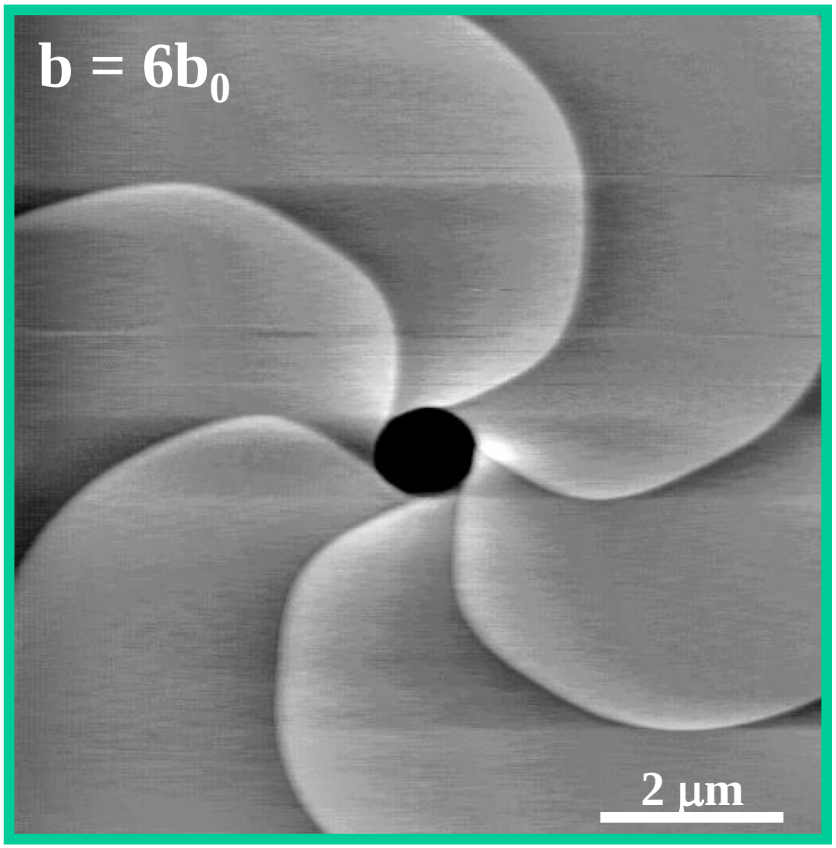


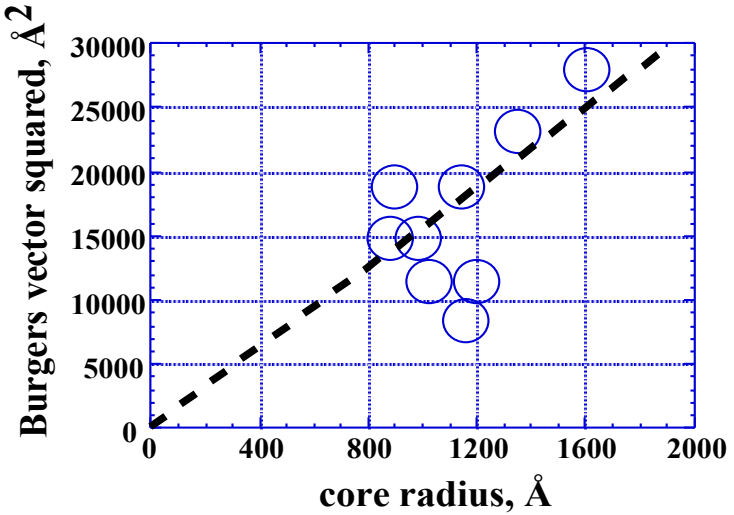
Defects: Micropipes



$$\frac{b^2}{r_o} = \frac{8\pi^2\gamma}{G}$$

$$\frac{b^2}{r_o} = 16\text{Å}$$

surface energy, $\gamma = 4$ J/m²
shear modulus, G = 200 GPa



Micropipes form to relieve strain around super-screw dislocations.

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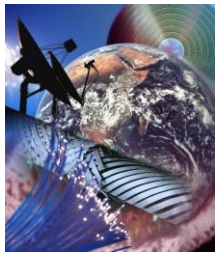
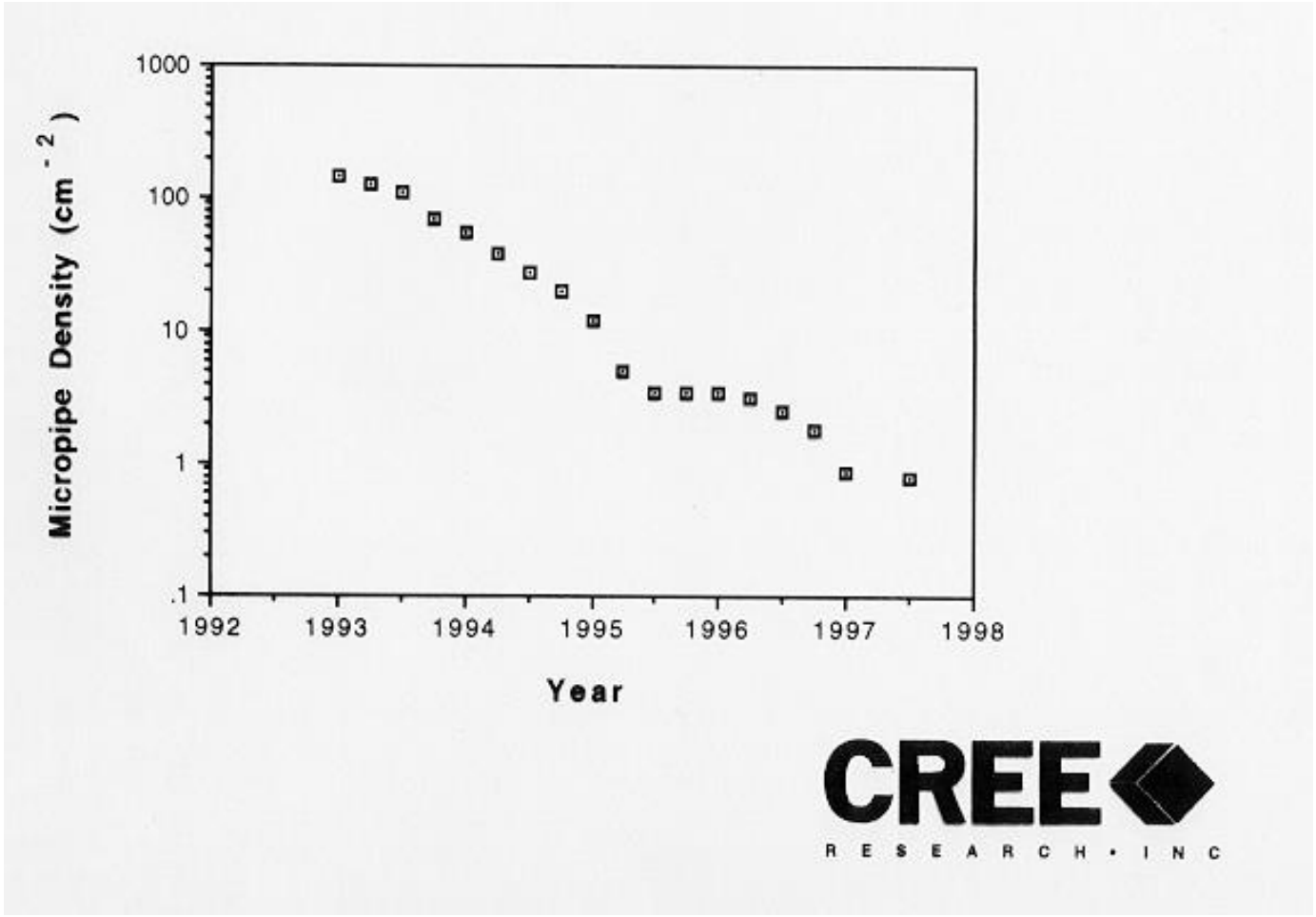


SiC: Micropipe Density vs. Year



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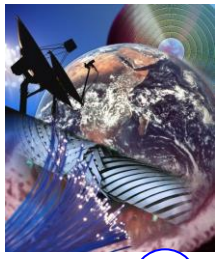
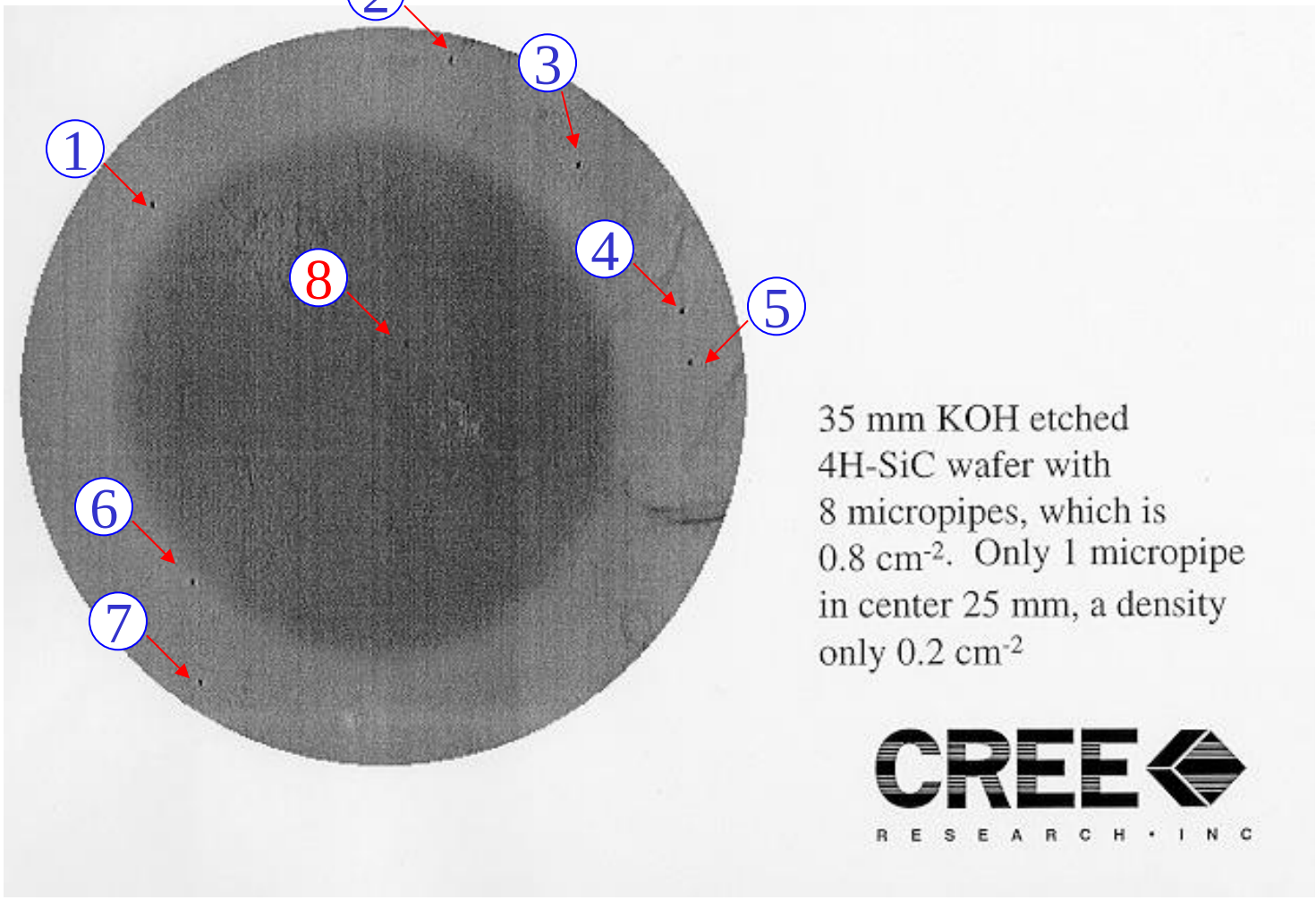


SiC: Record µPipe Density



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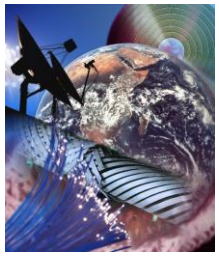
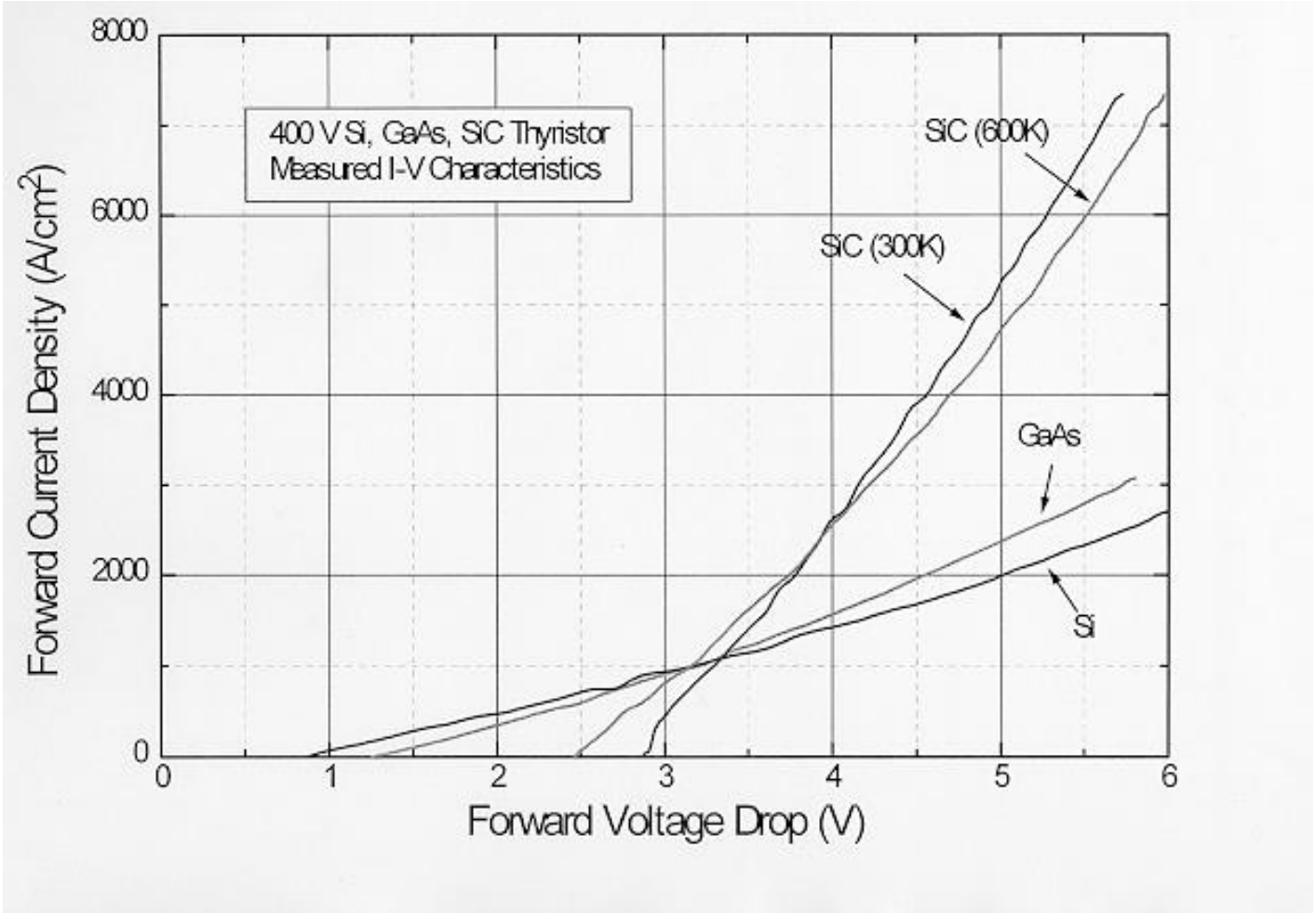


SiC Thyristor: Forward Voltage



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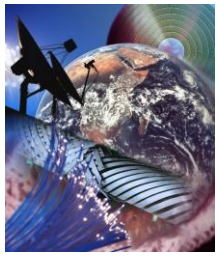
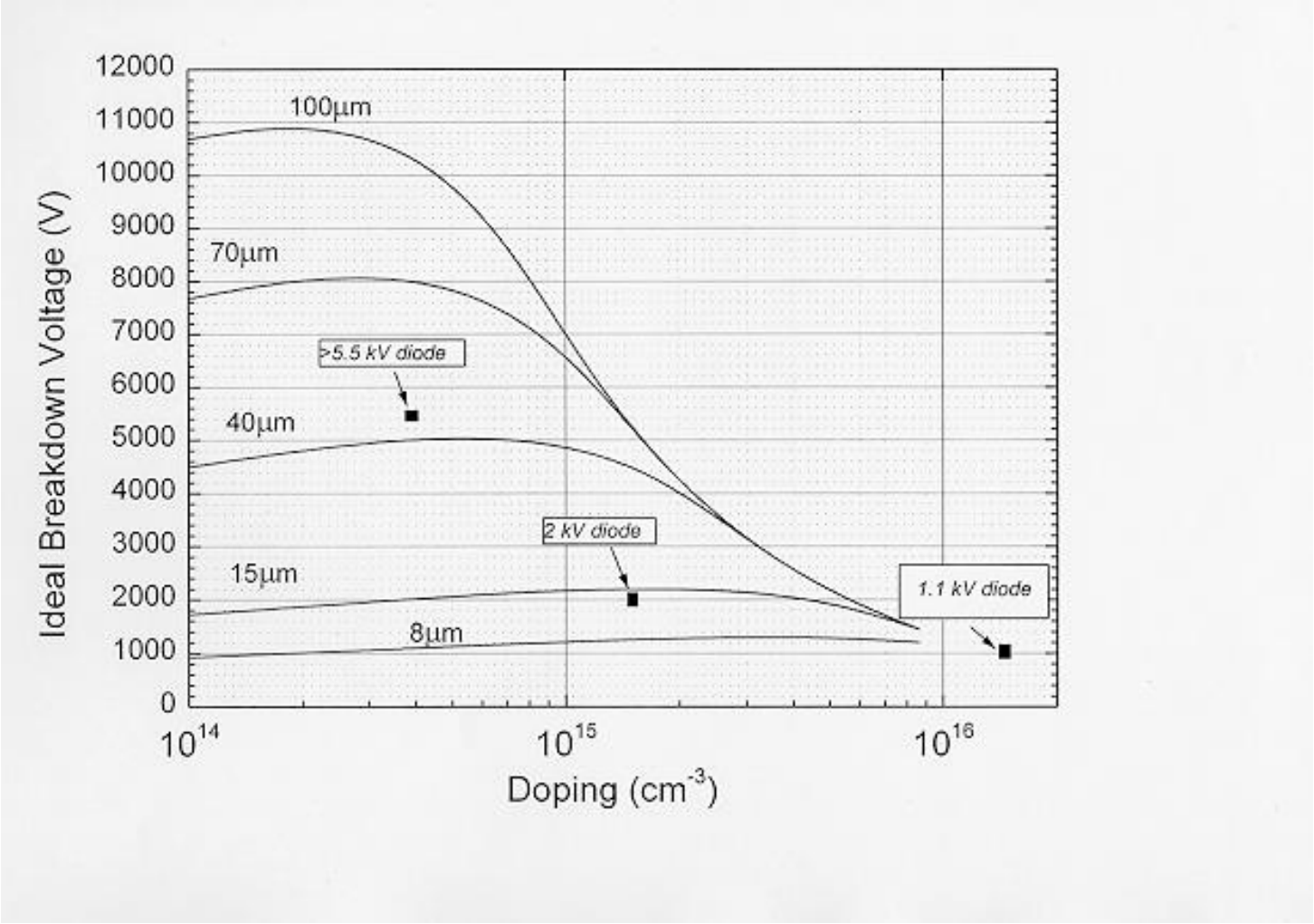


SiC Diode: Reverse Characterisitics



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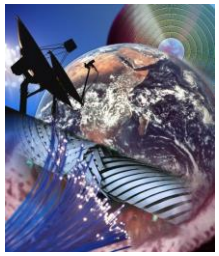

What About GaN & Diamonds?

See OutPost 8

“Why Diamonds are a Girl’s Best Friend!”