30 years of Silicon Carbide excellence in Kista – discover the unique SiC innovation hub and meet with founders and stakeholders.

My ~~The~~ history of Silicon Carbide and world class SiC research at KTH in Kista.

Anders Hallén, KTH

SiC material growth - some milestones

1824 — J.J. Berzelius
First to synthezise SiC

1885 — E.G. Acheson
Large scale synthesis of SiC
Carborundum

1907 — H.J. Round
First SiC LED

1955 — J.A. Lely
Sublimation growth of SiC

1977 — M. Tairov and V.F. Tsvetskov
Modified Lely growth or seeded sublimation growth

1987 — H. Matsunami
Step-flow epitaxy on off-axis substrates

1995 — E. Janzén, Linköping University
Hot wall CVD epitaxy

Cree, Inc. formed

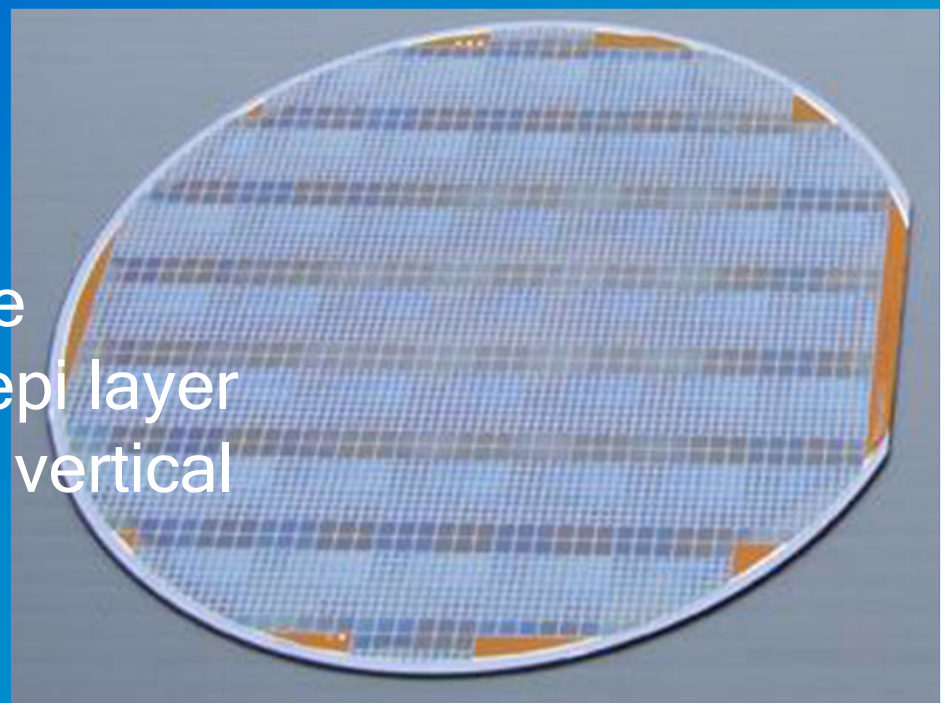
ICSCRM took off

SiC Wafers

High purity epitaxial layers using CVD

Epi thickness ≈1-100 µm
Grown off c-axis

Highly doped substrates (typically n-type)



- Device structures are implemented in the epi layer
- Power devices often vertical
- IC are lateral

KTH
School of ICT

More local and recent history

Fabrication of Si power devices, diodes and thyristors, at ABB Drives in Västerås was moved to Switzerland around 1989.

Instead, ABB Sweden should lead *emerging technologies* i.e. silicon carbide

Smaller SiC efforts started in Kista during early 90'ies: material, characterization and devices

1997 Swedish Foundation for Strategic Research (SSF) launched SICEP (Silicon carbide electronics program, 1997-2002).

SICEP involved Linköping University (LiU), Royal Institute of Technology (KTH) and Chalmers University (CTH).

From ”the farm to the fork” (ax till limpa)

About 20 PhD students.

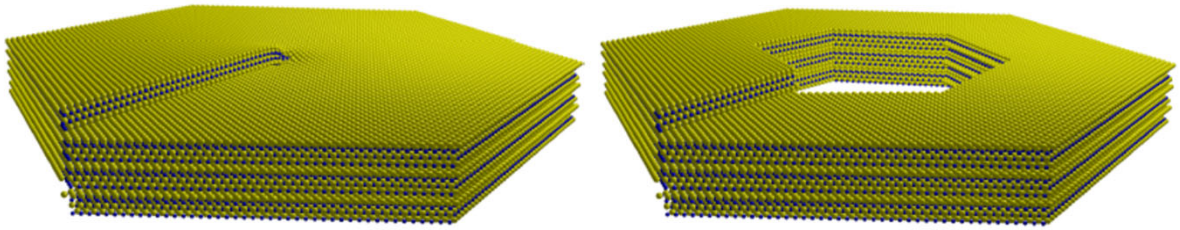
Very non-Swedish way of funding research.

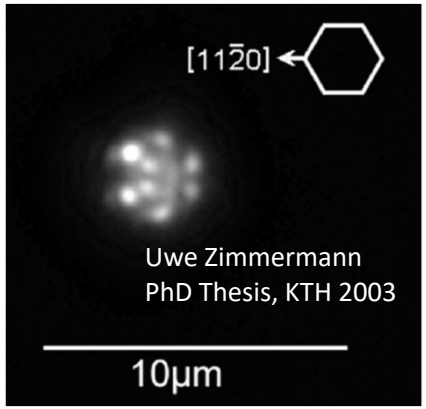
ABB supported SICEP via their own SCRIPT project and made massive investments in Kista.

Micropipes-the killer defect

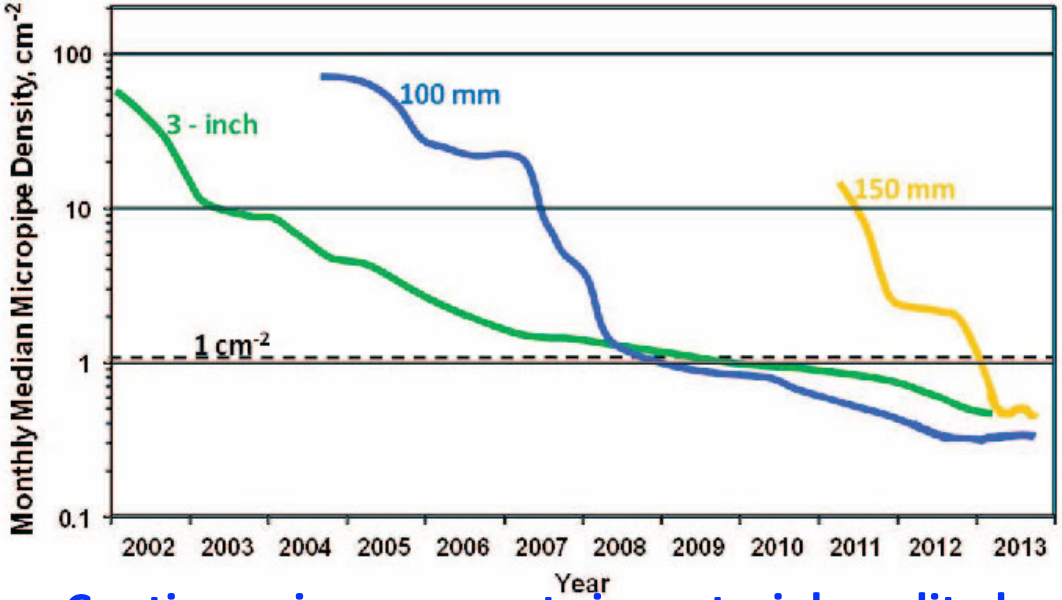
(Used to be the most severe threat to SiC material quality)

Closed screw dislocation **Micropipe**



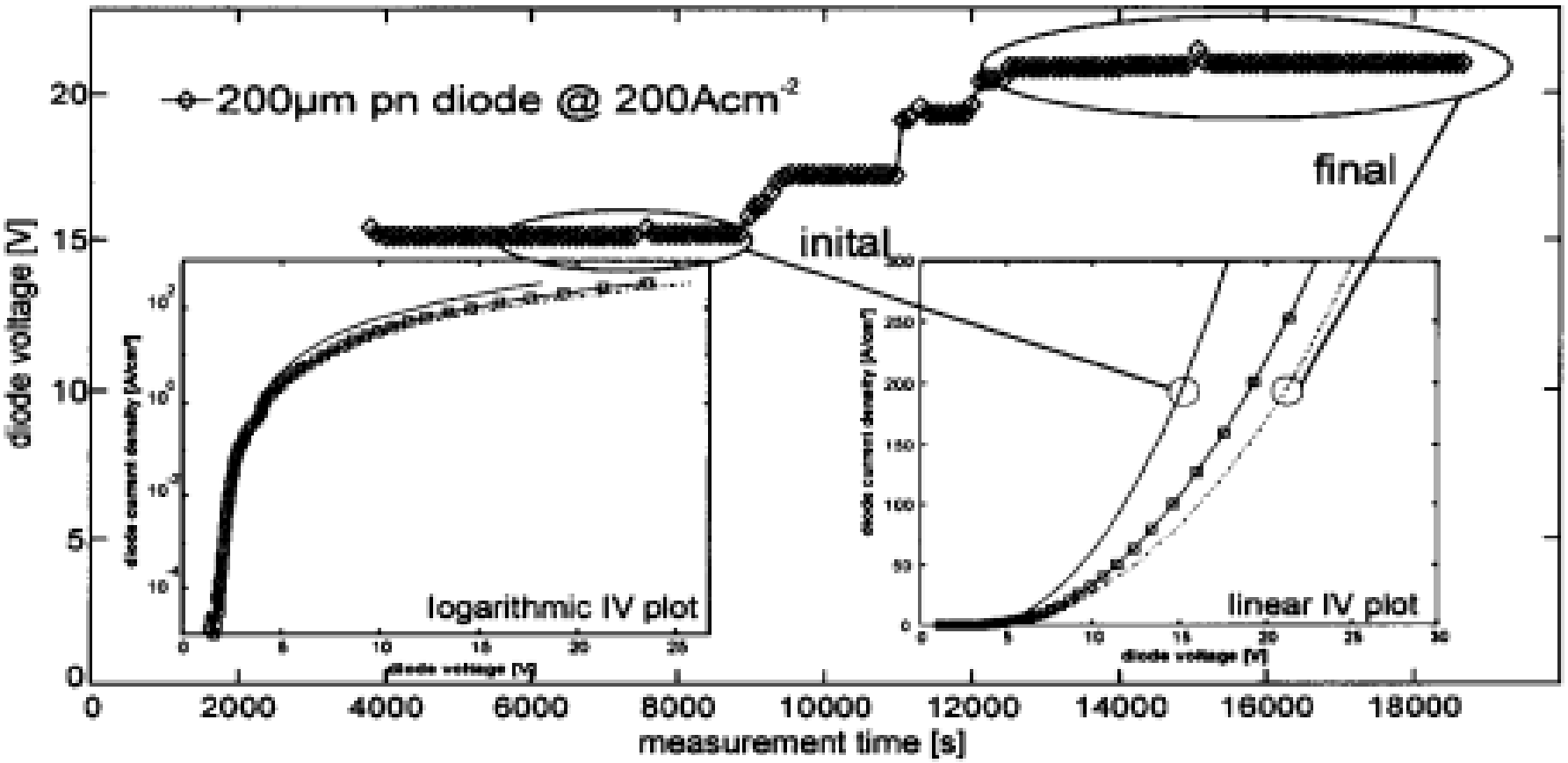


- Electroluminescence from micropipe at reverse bias.
- Catastrophic breakdown.



Continous improvments in material quality has reduced micorpipe density well below 1 cm^{-2} . No longer a problem??

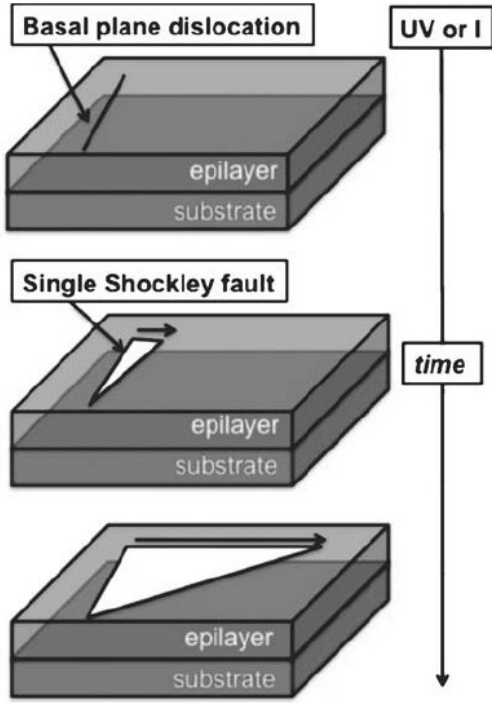
Bipolar Degradation



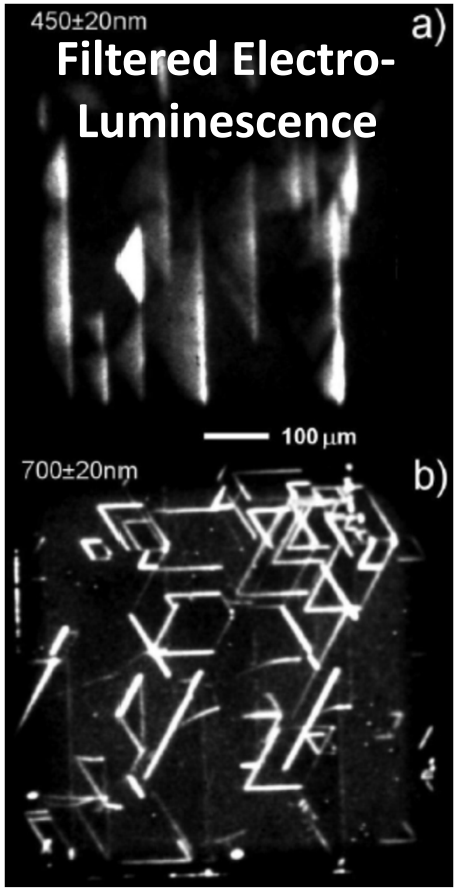
Uwe Zimmermann et al.
Materials Science Forum 389-393, 1285 (2002)

Bipolar Degradation

A. O. Konstantinov and H. Bleichner, Appl. Phys. Lett. **71**, 3700 (1997).

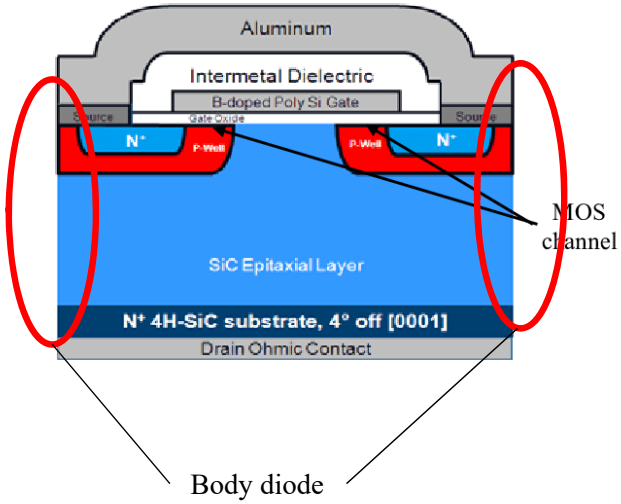


- Severe reliability issue, particularly for bipolar devices.
- Initiated by charge carrier recombination at basal plane dislocations (BPD).



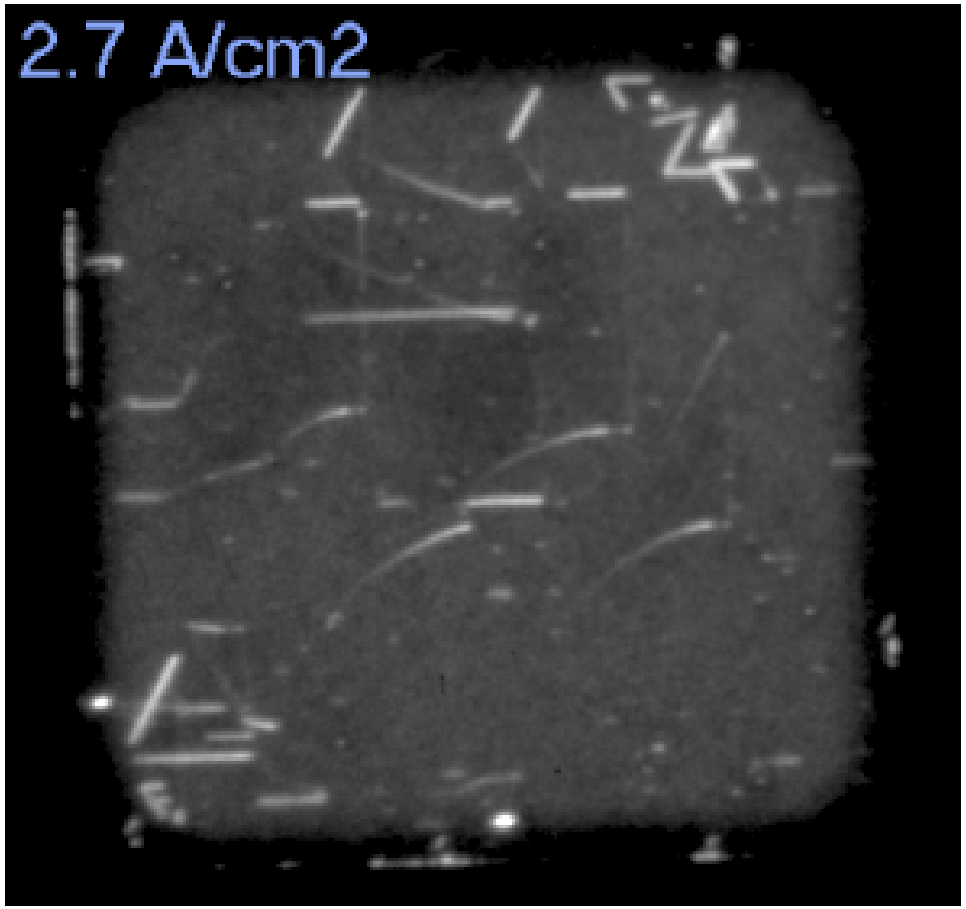
Pirouz, Galeckas, January 2011
ECS Transactions 41(8):225-236

a) 450 nm EL from SF planes.
b) 700 nm EL from partial edge dislocations



- Still a reliability issue, also for unipolar devices (MOSFET) due to the parasitic pin diode.
- Reducing the BPD by inserting buffer layer between substrate and epi.

Galeckas, Linnros, Pirouz, APS 2003
(Slide in courtesy of Augustinas Galeckas, UiO)



t=4.4 s, T=30C, 2.8/7/14 A/cm2.

Nucleation and glide of dislocations in SiC require stresses of GPa and ~1000K temperatures

Energy needed to promote dislocation glide comes from *e-h* recombination:

Recombination
Enhanced
Dislocation
Glide

Degradation phenomenon: DEVICE or MATERIAL problem?

ANIMATION #

ABB terminated their SiC activities 2001 and closed their site in Kista.

SICEP provided support for a few more years, but SiC activities somehow kept the momentum in Kista.

More device related research gained funding.

Start-ups TranSiC (2005) and Ascatron (2011) where formed.

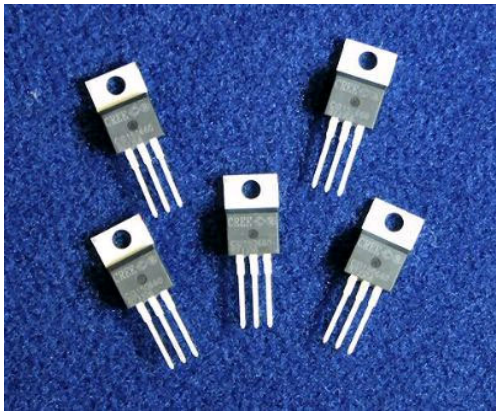
More since a few years KISAB is established.

The SiC momentum in Kista is maintained!

30 year development of SiC wafers and electronic devices

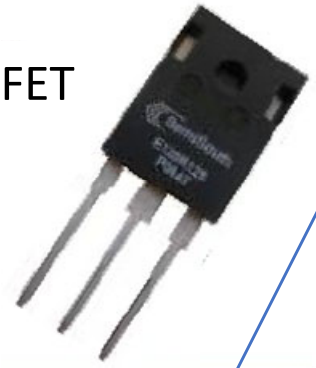
Electronic Power Devices

Schottky diodes

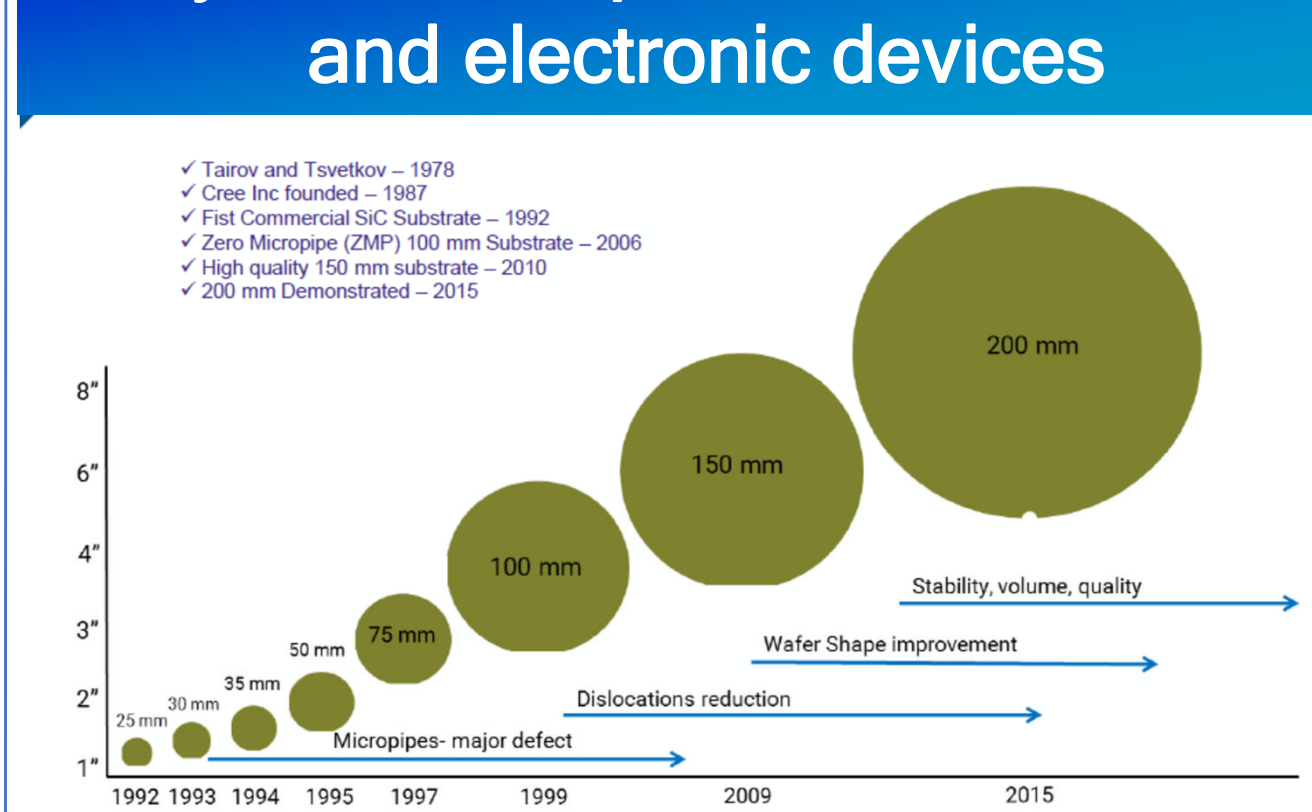


BJT

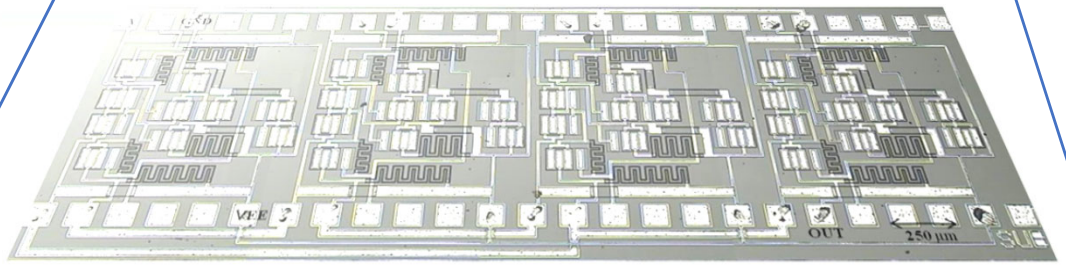
MOSFET



Bipolar power
pin diodes,
thyristors,
IGBT



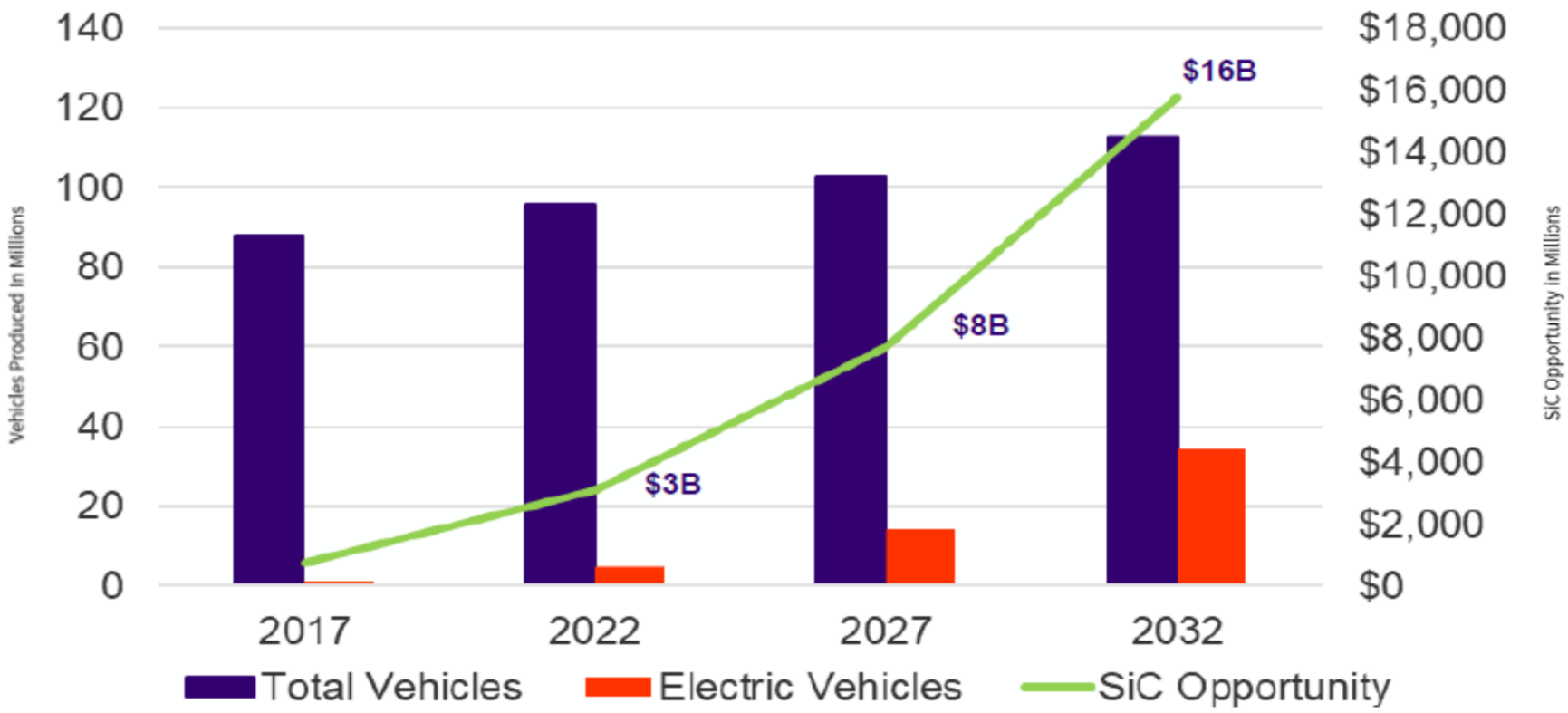
High temperature IC



Sensors and detectors

Even Modest EV Adoption Drives Significant Opportunity

SiC Driving a Multi-Decade Opportunity in EV and EV Infrastructure



*Source: Morgan Stanley and Cree Estimates

CREE Wolfspeed

SiC PhDs at KTH (>50)

Nils Lundberg, 1996
Thermally stable electrical contacts to 6H silicon carbide

Hans-Erik Nilsson, 1997
Theoretical and experimental study of vertical MESFETs in Si and SiC

Carl Mikael Zetterling, 1997
Silicon dioxide and aluminum nitride as gate dielectric for high temperature and high-power silicon carbide MOSFETs

Margareta Linnarsson, 1997
Compound semiconductors: defects and relocation of atoms during growth, sputtering and diffusion

Olof Tornblad, 1998
Physical modeling of on-state losses in bipolar Si and SiC power devices

Christer Fröjdh, 1998
Schottky barrier and Schottky barrier-based devices on Si and SiC

Martin Domeij, 1999
Dynamic avalance in Si and 4H-SiC power diodes

Rémy Kolessar, 2001
Compact Modeling of Si and SiC Power Diodes

Paolo Pelligrino, 2001
Point Defects in ion implanted Silicon and Silicon-Carbide

Denny Åberg, 2001
Capacitance spectroscopy of point defects in silicon and silicon carbide

Erik Danielsson, 2001
Processing and characterization of GaN/SiC heterojunctions and SiC bipolar transistors

Sang-Kwon Lee, 2002
Processing and Characterization of silicon carbide (6H- and 4H-SiC) contacts for high power and high temperature device applications

Fanny Dahlquist, 2002
Junction barrier Schottky rectifiers in silicon carbide

Ewa Mårtensson, 2003
Modelling electrical properties of composite materials

Uwe Zimmermann, 2003
Design, processing and characterization of silicon carbide diodes

Martin Janson, 2003
Hydrogen Diffusion and Ion Implantation in Silicon Carbide

Antonio Martinez, 2003
Hole transport in 4H-SiC and GaN

Hisaomi Iwata, 2003
Stacking faults in silicon carbide

Sang-Mo Koo, 2003
Design and process issues of junction- and ferroelectric-field effect transistor in silicon carbide

Wei Liu, 2004
Electro-thermal simulations and measurements of silicon carbide power transistors

Mats Hjelm, 2004
Monte Carlo simulations of homogeneous and inhomogeneous transport in silicon carbide

John Österman, 2004
Characterization of electrical properties of 4H-SiC by imaging techniques

Paulius Grivickas, 2004
Optical studies of carrier transport and fundamental absorption in 4H-SiC and Si

Hanne Kortegaard Nielsen, 2005
Capacitance transient measurements on point defects in silicon and silicon carbide

Björn Ållebrand, 2005
On SiC JFET converters: components, gate-drives and main-circuit conditions

Kent Bertilsson, 2005
Simulation and Optimization of SiC Field Effect Transistors

Maciej Wolborski, 2006
Characterization of dielectric layers for passivation of 4H-SiC devices

Hyung-Seok Lee, 2008
Fabrication and characterization of silicon carbide power bipolar junction transistors

Muhammad Usman, 2011
Impact of ionizing radiation on 4H-SiC devices

Reza Ghandi, 2011
Surface-passivation effects on the performance of 4H-SiC BJTs

Romain Esteve, 2011
Fabrication and Characterization of 3C- and 4H-SiC MOSFETs

Benedetto Buono, 2012
Simulation and characterization of silicon carbide power bipolar junction transistors

Dimosthenis Peftitsis, 2013
On gate drivers and applications of normally-on SiC JEFETs

Luigia Lanni, 2014
Silicon carbide bipolar technology for high temperature integrated circuits

Jang-Kwon Lim, 2015
Simulation and electrical evaluation of 4H-SiC junction field effect transistors and junction barrier Schottky diodes with buried grids

Georg Tolstoy, 2015
High-Efficiency SiC Power Conversion: Base Drivers for Bipolar Junction Transistors and Performance Impacts on Series-Resonant Converters

Sethu Suvanam, 2017
Radiation hardness of 4H-SiC devices and circuits

Diane Sadik, 2017
On reliability of SiC power devices in power eelctronics

Arash Salemi, 2017
Silicon Carbide Technology for High- and Ultra-High-Voltage Bipolar Junction Transistors and PiN Diodes

Raheleh Hedayati, 2017
High-temperature analog and mixed-signal integrated circuits in bipolar silicon carbide technology

Saleh Kargarazzi, 2017
High temperature bipolar SiC power integrated circuits

Hossein Elahipanah, 2017
Design optimization and realization of 4H-SiC bipolar junction transistors

Ye Tian, 2017
SiC readout IC for high temperature seismic sensor system

Erik Velander, 2017
On gate drivers for MOS-controlled power devices and dv-dt filters for train traction converters

Yafan Zhang, 2018
Multiphysics characteriazation of SiC power modules

Shuoben Hou, 2019
Silicon Carbide High Temperature Photodetectors and Image Sensor

Juan Colmenares, 2019
Extreme implementations of wide bandgap semiconductors in power electronics

Mattias Ekström, 2019
SiC CMOS and memory devices for high-temperature integrated circuits

Waqar Hussain, 2019
Silicon carbide radio circuits in silicon carbide bipolar technology

Arash Risseh, 2019
Waste-heat recovery using thermoelectricity and silicon carbide power electronics

Muhammad Shakir, 2019
Process design kit and high-temperature digital ASICs in silicon carbide

Keijo Jacobs, 2020
Silicon-Carbide-Based High-Voltage Submodules for HVDC Voltage-Source Converters

Daniel Johannesson, 2021
Ultrahigh-voltage silicon carbide device performance, requirements, and limitations in power applications

Ilka Jahn, 2021
Protection for Multiterminal HVDC grids-a digital contribution

Present PhD students in Kista

Alex Metreveli, Zimo Yuan and Xiaofan Ma