Past, Present, and Future of Radiation Effects Education

Professor Ron Schrimpf and Professor Ken Galloway

Institute for Space and Defense Electronics

Vanderbilt University

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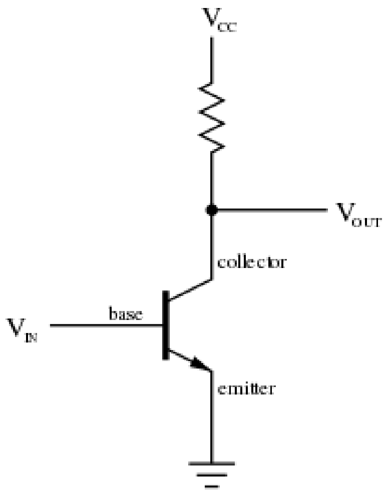
Historical Perspective ~ 1950s

- Nuclear weapons under development by a number of countries
- Nuclear reactor - a great hope for a future source of power
- Research on neutron displacement effects in reactor structural components and degradation of electronic piece-parts used in reactor control circuitry
- Semiconductor industry started following ~1947 invention of transistor
- Great interest in exploiting the transistor, not only in computers, but also in military and space electronics
- Sputnik 1 – October 1957
- Little known and much to be learned



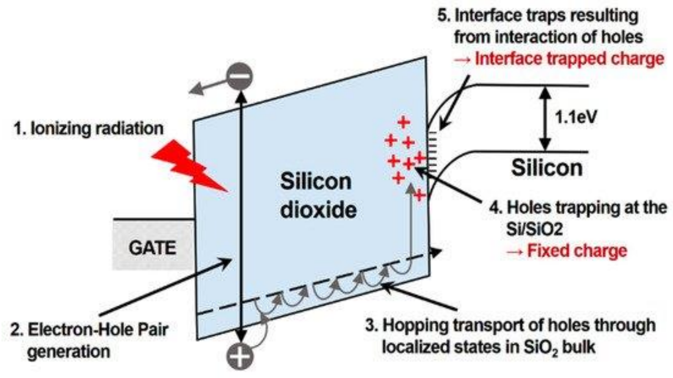
Historical Perspective ~ 1960s

Honolulu 1450 km away

- July 9, 1962 – Starfish, an experimental U.S. nuclear weapon detonated
- October 1962 – several similar Soviet nuclear events
- Nuclear contamination of the exo-atmosphere (Van Allen belts)
- February 1963 - accumulating radiation damage caused transistor failure in Telstar 1 – the first commercial communications satellite
- Prior to this, rad-effects studies was primarily concerned with effects on semiconductor bulk material

Historical Perspective – 1960s, 1970s

- Transient radiation effects, neutron damage – mostly bipolar devices
- ~ 1958 – neutron effects on BJT gain – Messenger and Spratt
- ~ 1960 invention of the integrated circuit – Noyce, Kilby
- ~ 1964 – discovery of TID effects in MOS devices – Hughes
- Early 1960s, (SSI) tens of transistors/chip
- In 1962, total IC market of $4 million, U.S. DoD
- 1965 - Moore's Law articulated
- Late 1960s - (MSI) hundreds of transistors/chip
- 1971 - Intel released a 4-bit microprocessor (4004) with 2,300 transistors
- 1970s – TID MOS basic mechanisms - charge generation, charge transport, interface charge buildup, separating N_{it} and N_{ot}
- 1975 – SEUs first observed in satellite systems – Smith, Holman, Binder
- 1979 – sea-level cosmic ray single event upset in electronics – Ziegler

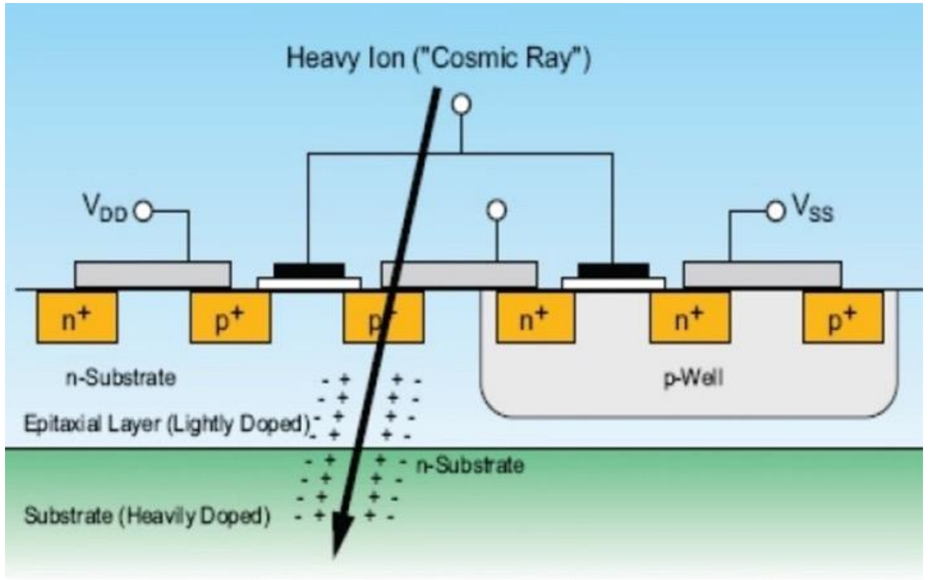


Historical Perspective - First NSREC 1964

- Held July 20-23, 1964 at the University of Washington, Seattle
- Evolved from AIEE and IRE/AIEE Meetings in 1962 and 1963
- ~215 attendees – Chaired by John Winslow and Bill Price
- > 50 papers presented

Historical Perspective – 1980s, 1990s

- More MOS TID basic mechanisms research – Many …..
- 1986 – 1-megabit RAM with more than one million transistors introduced
- ~ 1986 – Single event burnout (SEB) of power transistors – Waskiewicz, *et al.*
- 1989 – microprocessor chips passed the million-transistor mark
- ~ 1991 – ELDRS (enhanced low dose rate sensitivity) – Enlow, *et al.*
- Rapid growth in single event research: SEB, SET, multi-bit upsets, etc.



Historical Perspective - First RADECS 1989

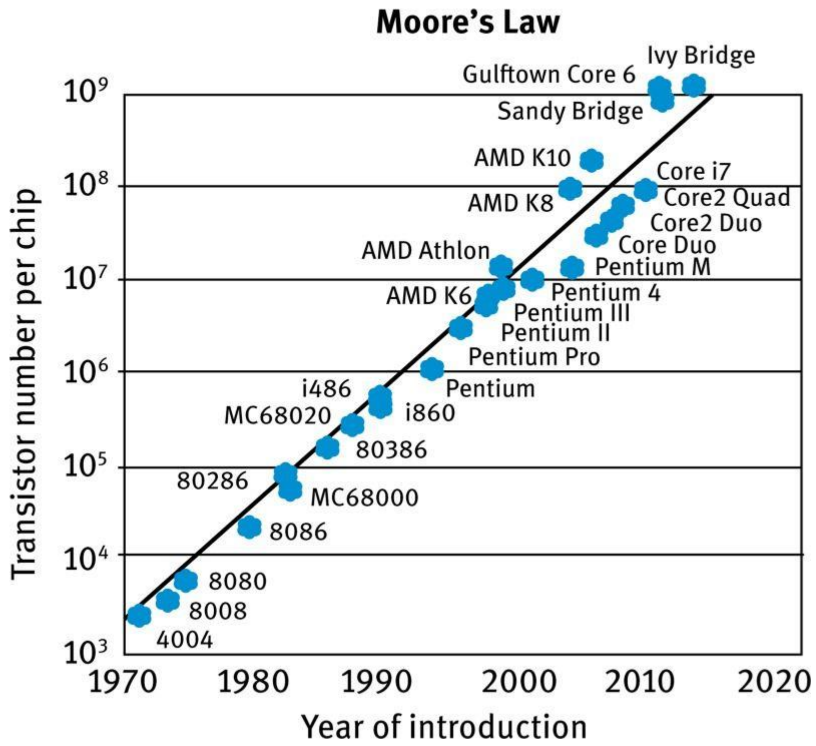
- Held at La Grande-Motte, France

Historical Perspective – 1990s

- **Rad-Effects Community**
  - ELDRS (enhanced low dose rate sensitivity)
  - Isolation technology: LOCOS to STI and SOI technology
  - Role of hydrogen in the build-up interface trapped charge
  - Ultrathin SiO_2 gate oxides
  - Rapid growth in single event research: SEB, SET, multi-bit upsets
- **Commercial/Industrial World**
  - LOCOS to shallow trench isolation (STI)
  - Submicron silicon-gate CMOS
  - MOS gate oxides < 10nm thick, gate stacks including high-K gate dielectrics
  - Multiple-gate structures

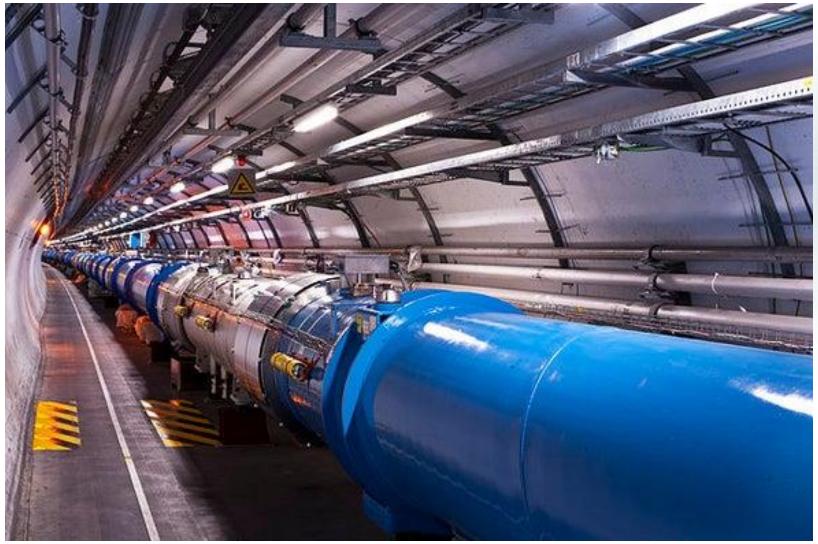
Historical Perspective – 2000s

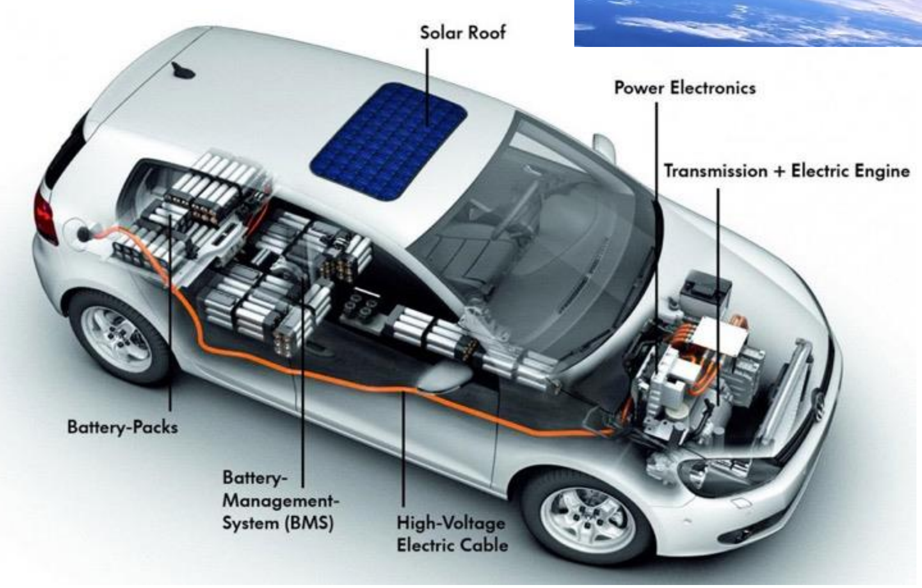
- SiGe, SOI, ultra-thin gate dielectrics, high-K gate dielectrics, FinFETs, etc.
- All of the above technologies have unique, interesting rad-effects challenges
- Rad-hard by design (RHBD) increases in importance
- 2005, microprocessor chips pass the billion-transistor mark
- On track for 7nm (and below) chips
- Moore's Law continues – will it ever end?



Today: Growing demand for radiation effects scientist and engineers

- Space
- Defense
- Terrestrial reliability
- Accelerators





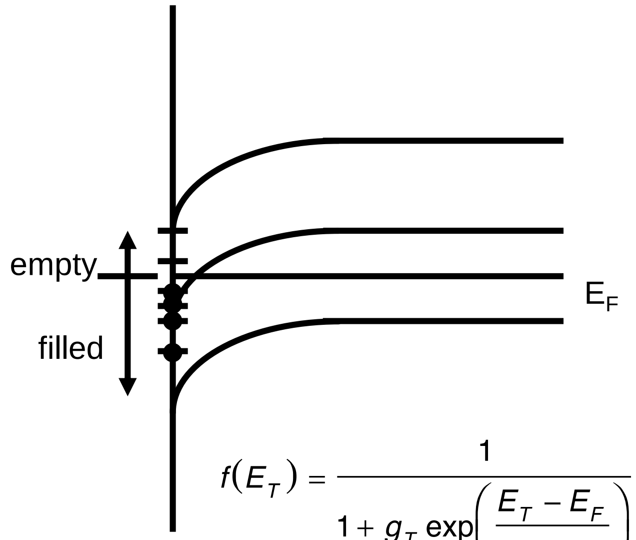
What radiation-effects engineers do…

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

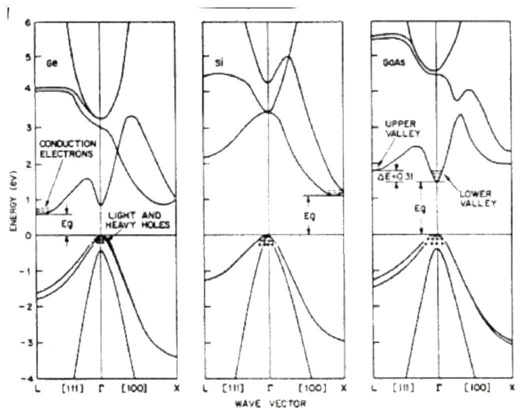
$$\nabla \cdot \mathbf{B} = 0$$

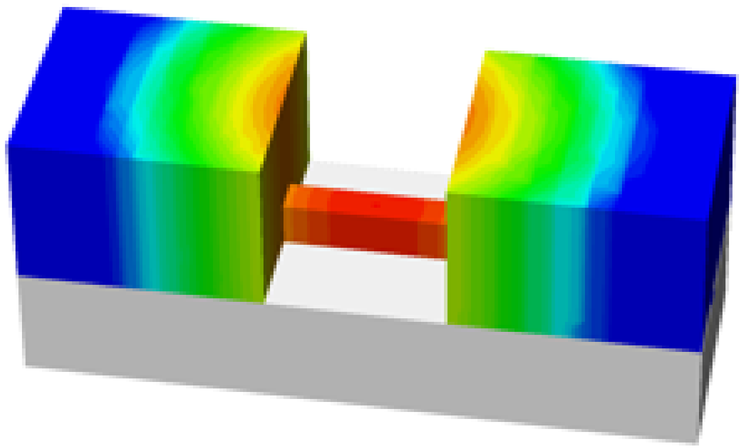
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{j} + \frac{1}{c^2}\frac{\partial \mathbf{E}}{\partial t}$$



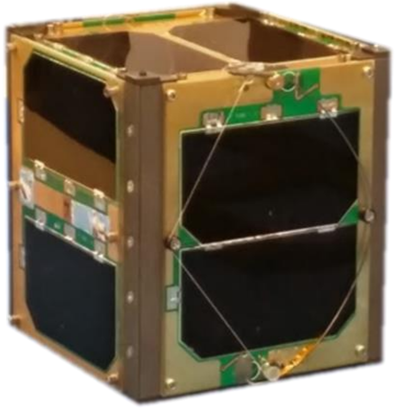
$$f(E_T) = \frac{1}{1 + g_T \exp\left(\frac{E_T - E_F}{kT}\right)}$$

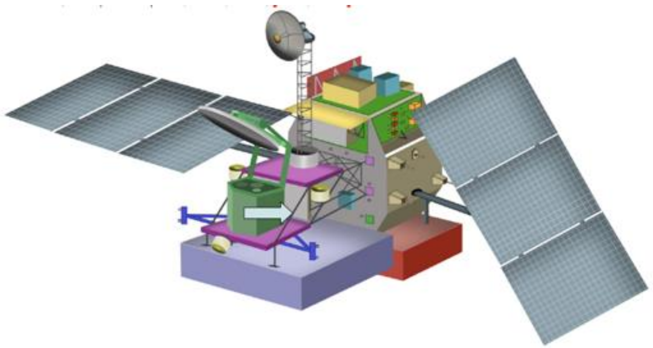


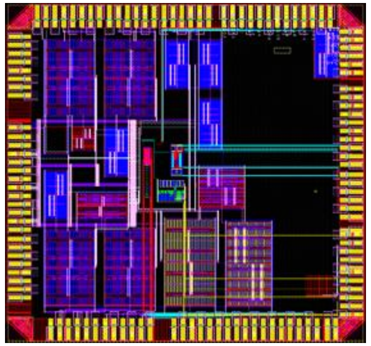


What people want…

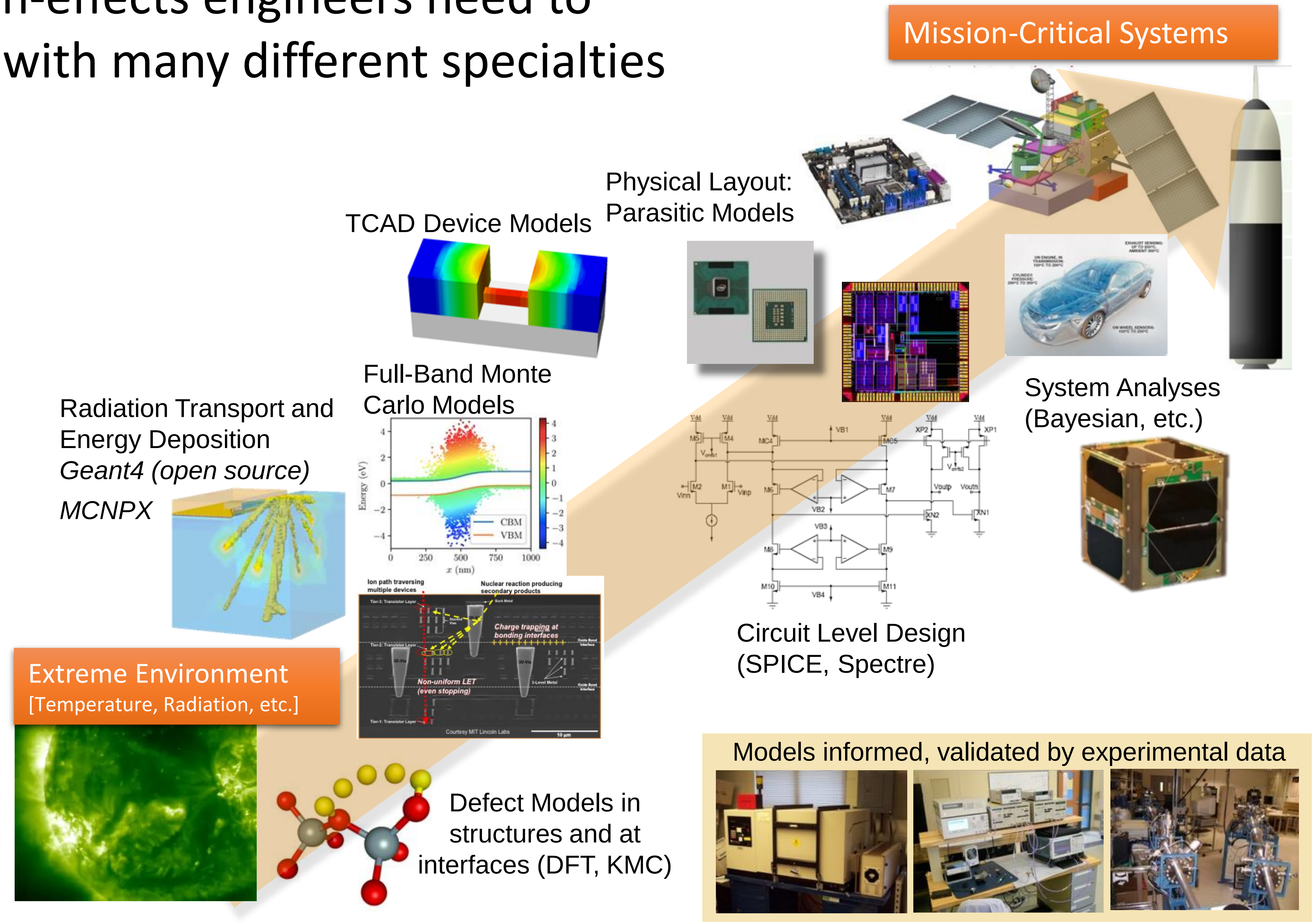
- Does it work?







Radiation-effects engineers need to interact with many different specialties



Physics to Circuits?

Physical Models:
- Process/Material Characteristics
- Physics of Radiation Interactions
- Radiation Response Mechanisms

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Engineering Design:
- Compact Models
- EDA Tools
- Hardened Devices/Layout
- Hardened Circuit Topologies

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System Response:
- Performance Degradation
- Upset Levels
- Operate Through
- Circumvention
- Survivability

Multiple knowledge and skills for radiation effects specialists

- Materials/Device Physics
- Circuits/IC Design
- Electrical Lab/Test
- Modeling/Simulation
- Systems Engineering
- Radiation-Specific Effects
- Radiation-Specific Test/Data/Standards

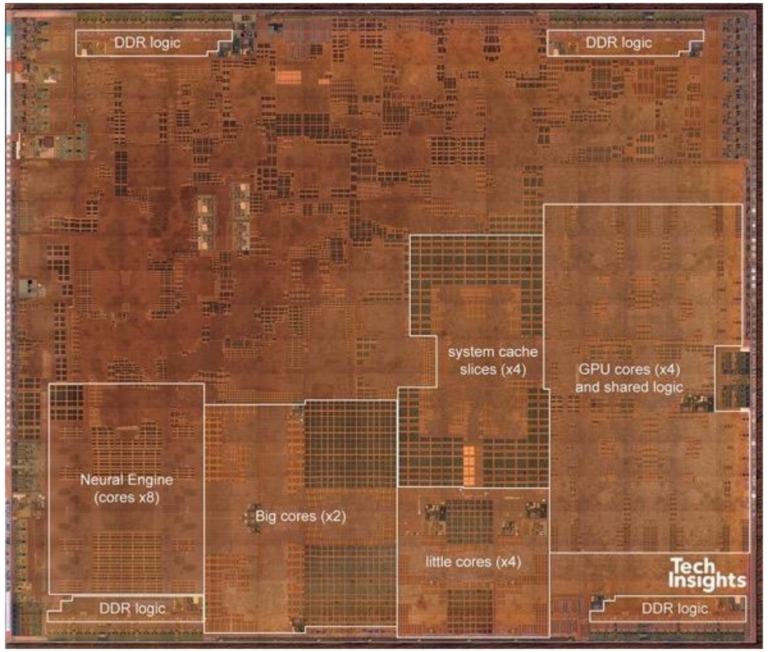
No one person does it all – it takes a team

Should I design a microprocessor using Schrodinger's equation?

$$\frac{-\hbar^2}{2m}\nabla^2\Psi(\mathrm{r}) + V(r)\Psi(\mathrm{r}) = E\Psi(\mathrm{r})$$

Kinetic Energy + *Potential Energy* = *Total Energy*

?



Apple A12 (techinsights.com)

Perhaps if we had more computing power…

- A brute-force approach is rarely the best
- Each level of abstraction offers opportunities
- How do we make them work together?

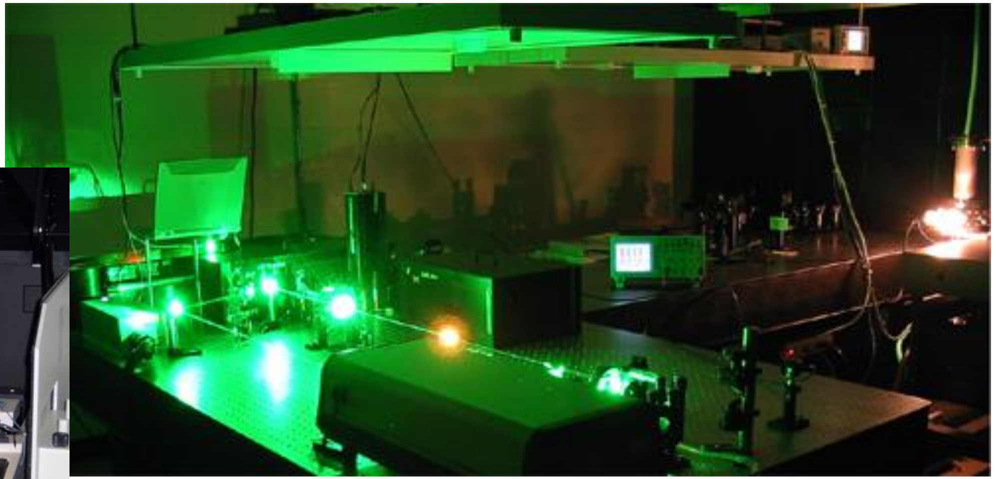
Vanderbilt Advanced Computing Center for Research and Education (ACCRE)

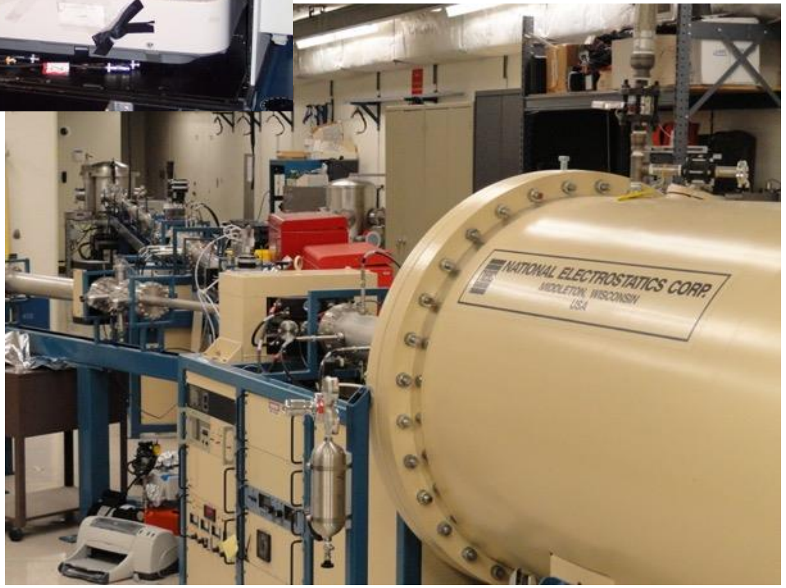
Why do radiation-effects engineers need to understand modeling?

- Understand mechanisms and principles
- Guide testing and experiments
- Increase confidence in results
  - Not all test results are correct
- Predict results for environments that cannot be obtained in test facilities
- Document processes throughout the system life cycle
- Reuse designs and IP
- Save money

Connections between experiments and modeling

- Radiation test facilities are approximations to actual environments
- Radiation-effects engineers need to understand how the test is related to the application
  - Characteristics of the facility
  - Characteristics of the devices
  - Characteristics of the models





Paths to a career in radiation effects

Just as there are multiple talents and skills needed there have been multiple paths to the workforce

- Technical training / degree (2 year program)
  - Test, characterization, qualification, etc.
- Undergraduate degree, master's (BS, MS)
  - Work throughout rad effects ecosystem,
  - On the job training
- Grad School specialization (Master's, Ph.D.)
  - Work throughout ecosystem
  - Research
  - Often entry into leadership and innovation roles

Past (1950s – 1970s): education of radiation effects scientist and engineers

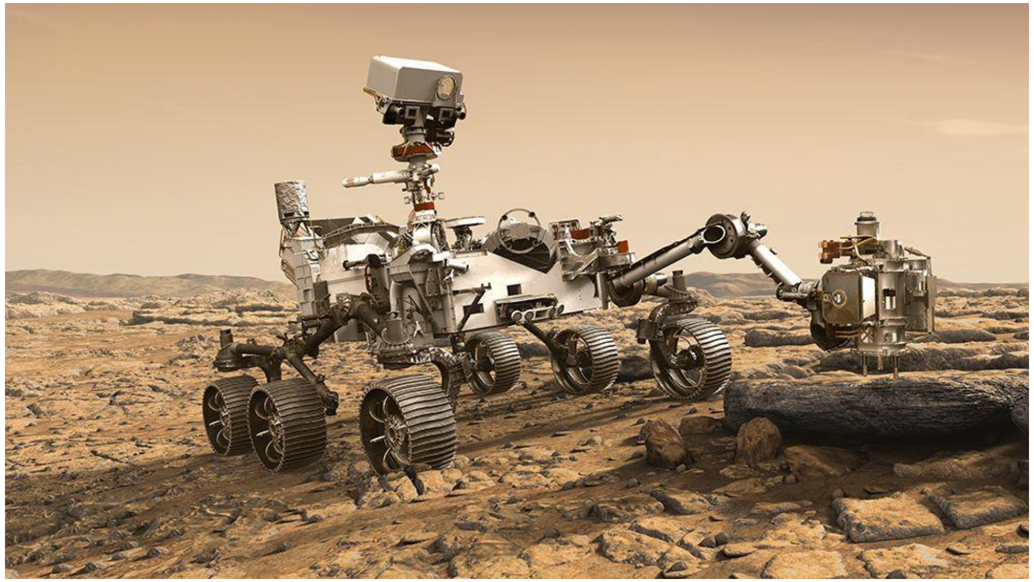
- Mostly trained in physics, some EEs
- Perhaps some knowledge of nuclear physics
- Jobs in 1950s and 1960s mostly defense related
- On the job training

Recent Past (1980s ⟶): education of radiation effects scientist and engineers

- Mostly electrical engineering, physics, or nuclear engineering backgrounds
- Course work in semiconductor device physics, IC design, materials, accelerator physics, etc.
- Most (BS, MS) enter workforce and receive on the job training
- Radiation effects specialization comes with graduate research (PhD) related to radiation effects
- Jobs in defense, space agencies,

  commercial space, research labs,

  government …..



Future: education of radiation effects scientist and engineers --- EU

- **RADSAGA**
  - Industry, universities, laboratories and test-facilities collaborating to train young scientists and engineers in all aspects related to electronics exposed to radiation
  - 15 Early-Stage Researchers trained through a well-defined program and structure --- PhD level program
  - Program nearing completion

- **RADMEP** - European Master in Radiation and its Effects on MicroElectronics and Photonics Technologies
  - Objective: educate students in those advanced technologies --- MS level
  - Goal # 1: to improve their career prospects
  - Goal # 2: respond to the needs of the industry, agencies and society
  - Program kicks off Fall 2021 --- MS level program

Master RADMEP

Future: education of radiation effects scientist and engineers --- USA

- **SCALE ---** Workforce development program funded by U.S. Department of Defense led by Purdue University
  - Mentoring, internship matching and targeted research projects for college students interested in three microelectronics specialty areas: **radiation-hardening**, heterogeneous integration/advanced packaging, and system on a chip
  - **Vanderbilt University** is radiation effects lead
  - Rad effects partners
    - Purdue, Georgia Tech, ASU, Brigham Young, St. Louis U., AFIT, ……………….
  - Goal: Work-ready graduates for U.S. defense and space industries
  - Emphasis on BS (1^{st} degree level)

Future: education of radiation effects scientist and engineers --- USA

Our crystal ball !

Future: education of radiation effects scientist and engineers --- USA

- GREAT job opportunities in radiation effects field
- Most 1st degree graduates will enter workforce without any specific radiation effects knowledge --- on the job training
- A few universities will offer a few 1st degree introductory courses in radiation effects --- this will depend on student demand, faculty availability and interest, and academic departmental emphasis
- Radiation effects research leaders will come from graduate programs (PhD) where faculty have a commitment to radiation effects research
- Existence of these rad-related research programs is dependent on research support from government and industry

Future: education of radiation effects scientist and engineers — Conferences

Technical Conferences are an important element for education and continuing education for radiation effects specialists

- IEEE NSREC, RADECS, ICREED (emerging in China)
- In the future …
  - Virtual?
  - In-Person?
  - Hybrid?

RADSAGA Graduates

WELCOME to the international radiation effects community …

Radiation effects science and engineering is important, interesting and challenging …

We hope you realize your dreams !