# **Small** Wonders in **Our** Future

Professor Umesh K. Mishra,

Director of the ONR Center for Advanced Nitride Electronics (CANE) and the AFOSR Center for Radiation Hard Physics

University of California, Santa Barbara

# Technology: The (Bad?) Answer to Society's Needs

- **MAXIMIZE COMPUTING POWER**
  - For geeks it provides the means of solving complex problems
  - For non-geeks (engineers?) It enhances the quality of life
    - Computer-controlled transportation (higher reliability, better ride)
    - Home entertainment (SONY play station)
    - Predicting weather

- **ENHANCE COMMUNICATIONS**
  - Voice communications over land lines is "almost-free,"
  - Wireless communications is increasingly the norm,
  - The internet has become integral in the life of the below 25 crowd,
  - Streaming video

- **ENHANCE ENTERTAINMENT**
  - Complex video games
  - High Definition Television
  - High Density DVD

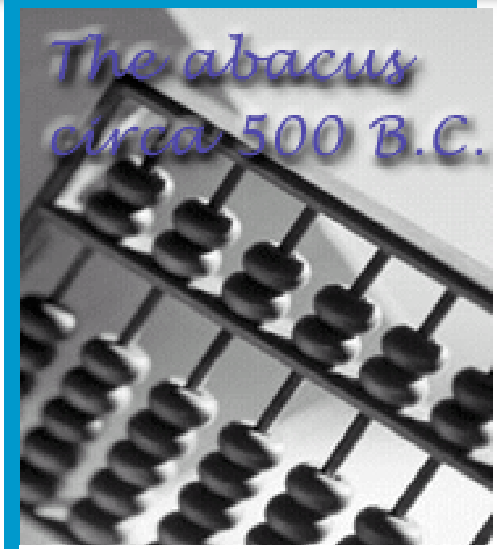
# The Possibilities of the Very Small: Feynman said it first…..

- ‘I would like to describe a field, in which little has been done, but in which an enormous amount can be done in principle…. manipulating and controlling things on a small scale’

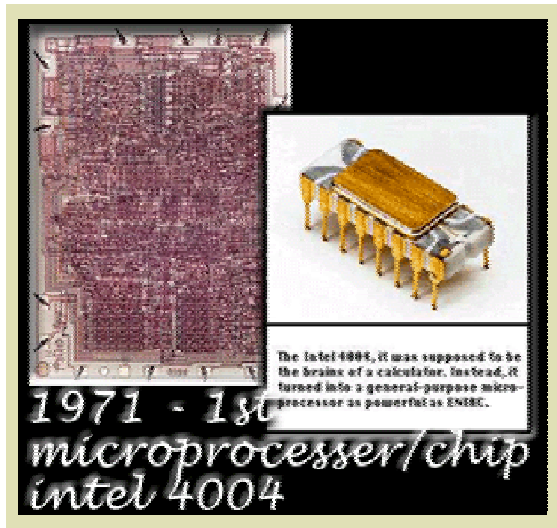
  Richard Feynman, Caltech 1959
  ‘There’s Plenty of Room at the Bottom’

  - Higher density of information: scaling down computer size
  - ‘New physics’: atoms on a small scale behave like *nothing* on the large scale
  - Formation of ‘micromachines’: machines that build machines
  - Creation of ‘designer materials’

# Just One Small Example of Size...

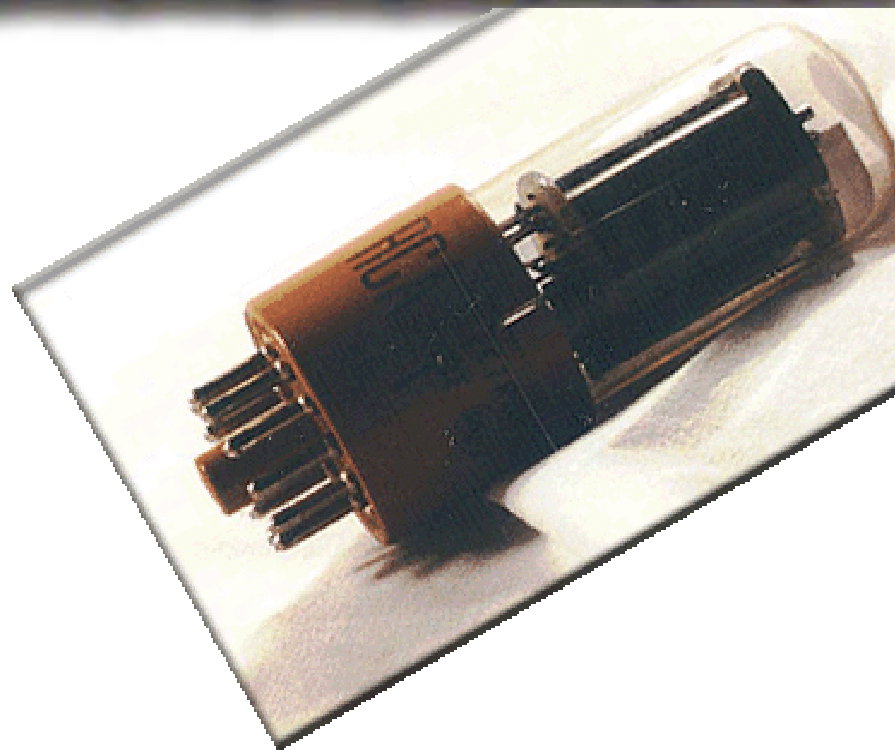








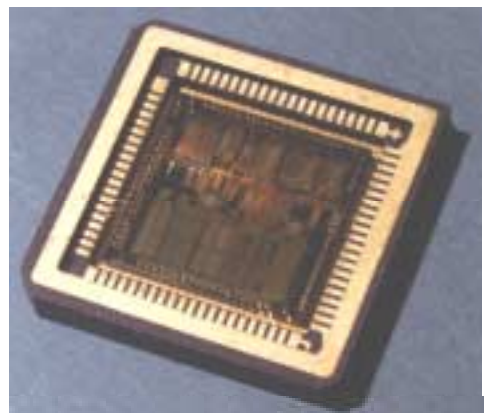
# History of Computing



# Higher Density Electronic Information

FIRST TRANSISTOR
1948

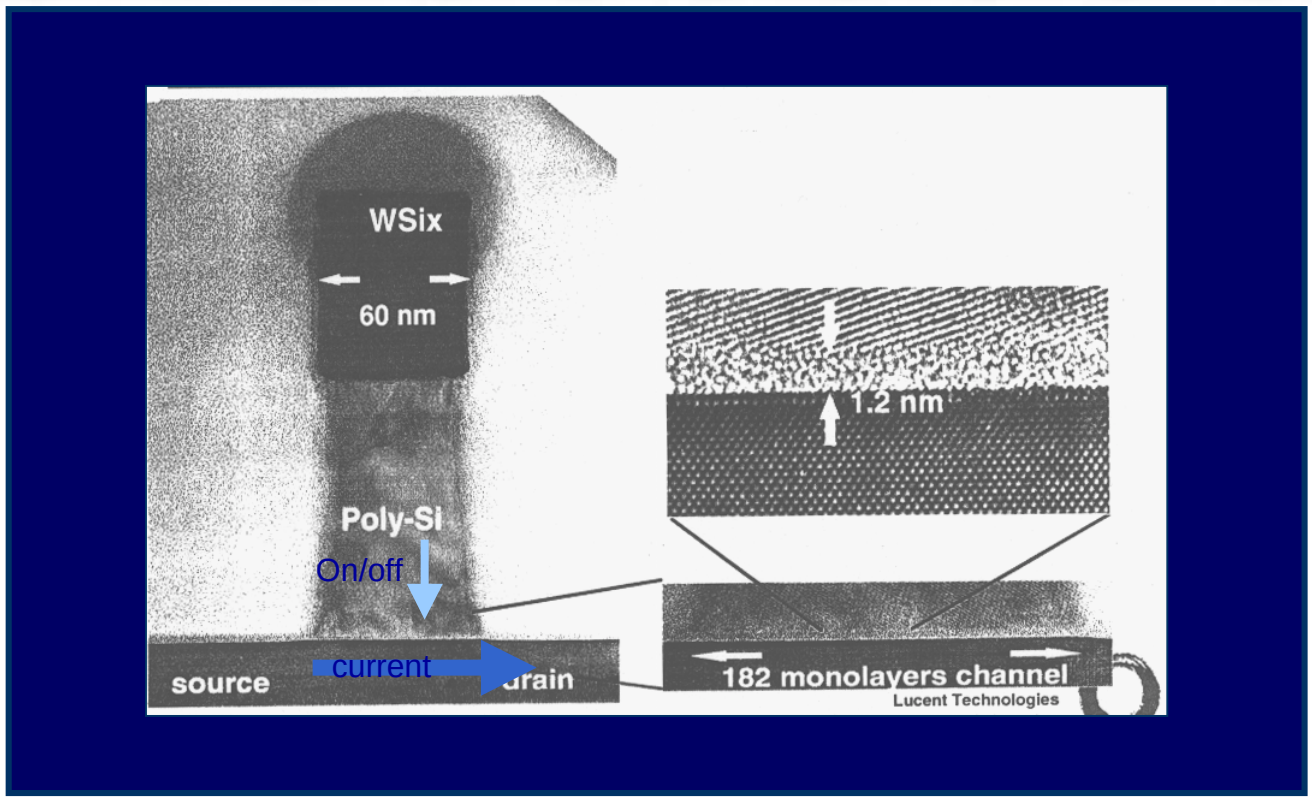
FIRST INTEGRATED CIRCUIT
1959



MICROPROCESSOR
CHIP

Scaling down to smaller switch sizes means more compact, lower cost computation, and information transfer

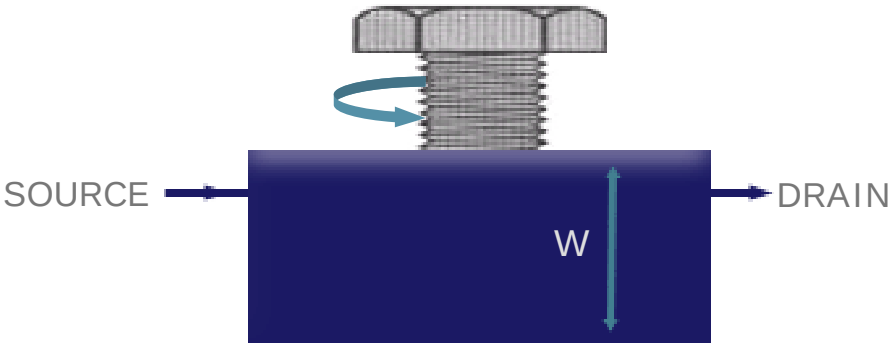
# Today's Transistor



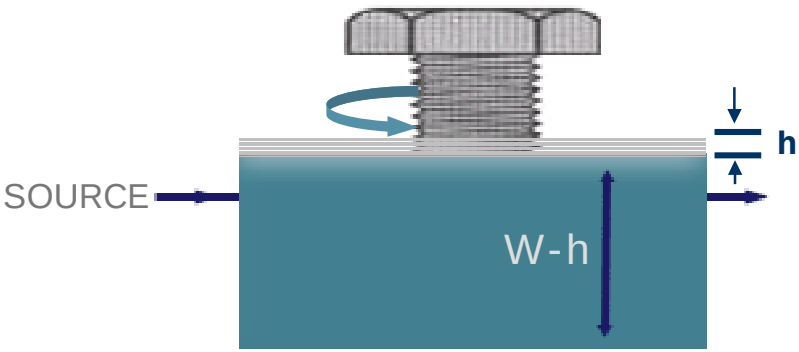

Lucent
courtesy R.E. Howard

# A Miraculous Engine – The Transistor

## THE ENGINE OF THE SEMICONDUCTOR

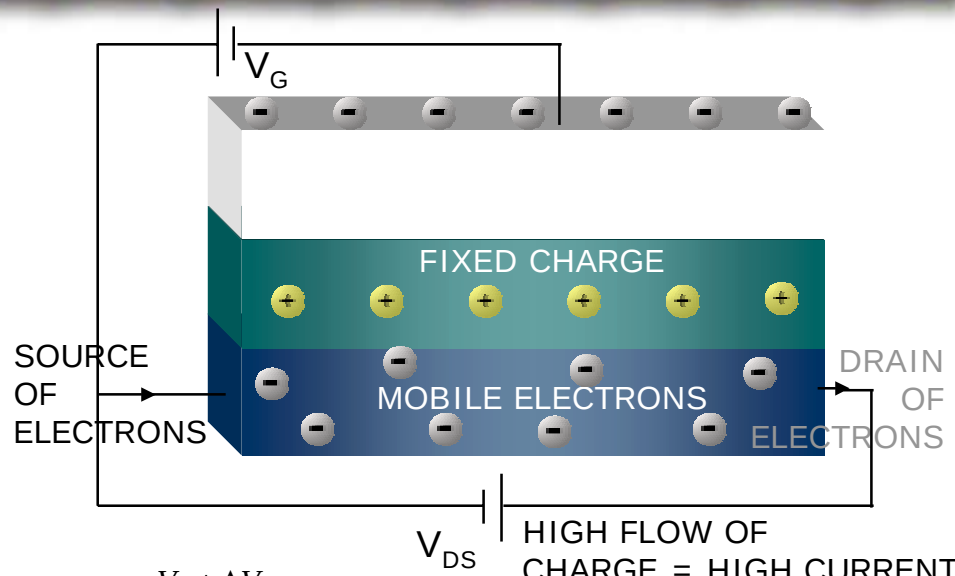



HIGH FLOW

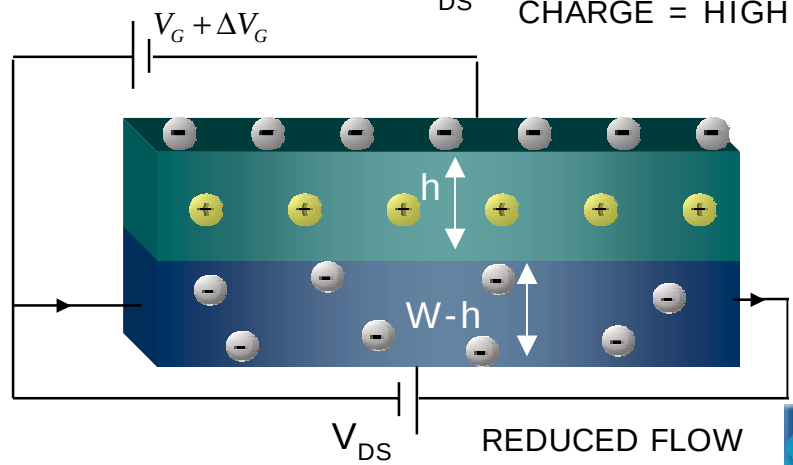



REDUCED FLOW

**CONTROL A LARGE FLOW OF WATER WITH MINIMUM WORK ON THE TAP**




HIGH FLOW OF CHARGE = HIGH CURRENT



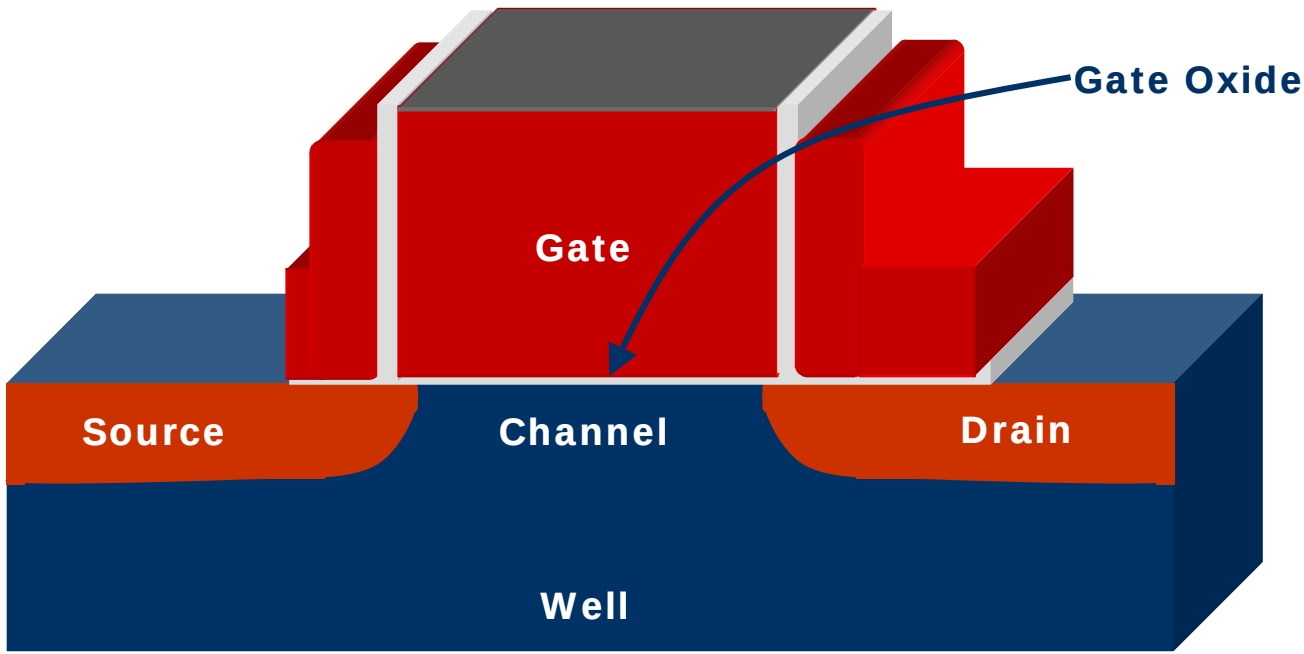

REDUCED FLOW

# Moore's Law

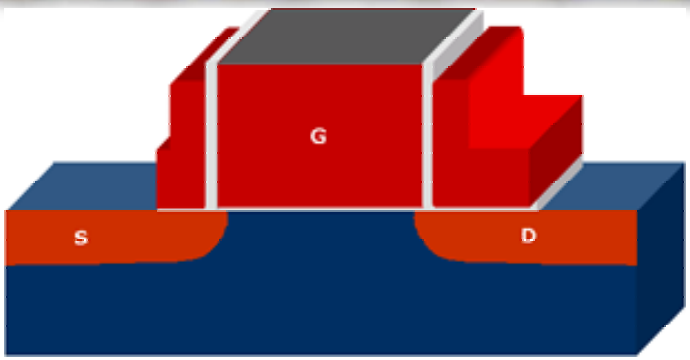
- Doubling of number of transistors per integrated circuit every 18- 24 months
  - First observed in 1965

- This expectation has driven Intel's research, development, and investments for the last 3 decades
  - Has enabled the incredible progress of the electronics industry

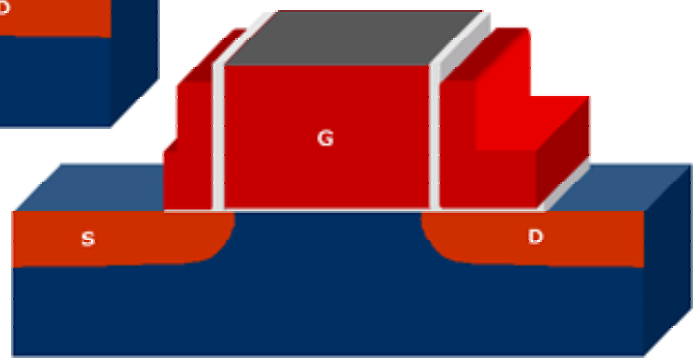
# What is a MOS Transistor?



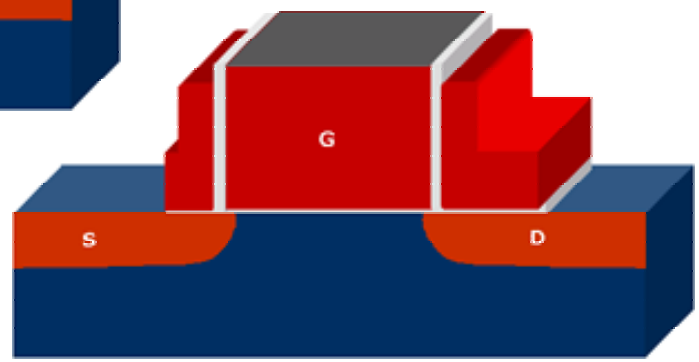
# How Does a MOS Transistor Work?




1. Transistor in “off” state




2. Applying a voltage ($V_T$) to the gate “inverts” the channel region, creating an electrical path between the source and drain



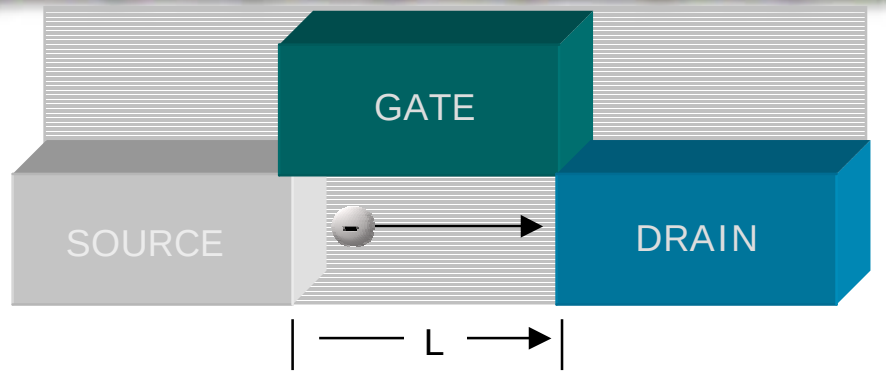

3. Applying a voltage to the drain pulls current-carriers across the channel, creating the drive current ($I_D$).

# Why Should We Want to Shrink Dimensions in Transistors

## 1. Faster Transistors

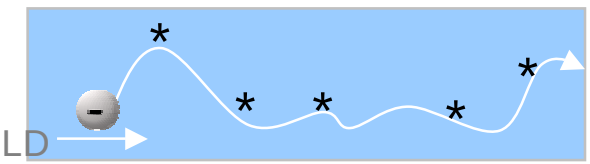
AS THE LENGTH OF THE GATE, L, BECOMES SMALLER THE ELECTRON GOES FASTER. NORMALLY AN ELECTRON TRAVELS AT A SATURATED VELOCITY, SIMILAR TO A TERMINAL VELOCITY THAT A PARACHUTER ACHIEVES.

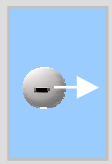
THE REASON IS THAT THE ENERGY GAINED THROUGH GRAVITY IS LOST TO THE AIR RESISTANCE (OR DRAG)




AIR RESISTANCE

GRAVITY



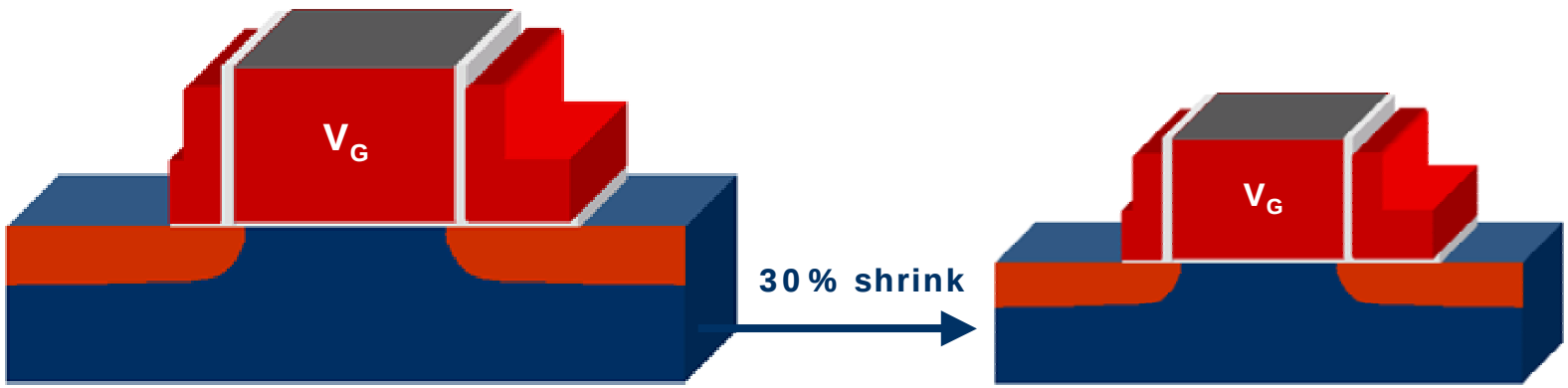
AS THE SEMICONDUCTOR SHRINKS, THE ELECTRON CAN MOVE WITH ALMOST NO COLLISIONS – BALLISTIC TRANSPORT.

HIGHER THE VELOCITY, SHORTER THE TIME FOR ELECTRONS TO TRANSIT FROM SOURCE TO DRAIN; FASTER THE TRANSISTOR

# Transistor Scaling

- The goal is to create smaller and faster transistors while retaining high level of performance.
- 30% linear shrink yields ½ transistor area

Transistor count doubles every two years



# Moore's Law Is Driven by Lithography

- 1960's — Contact printing
- 1970's — Projection printing
- 1980's — Wafer steppers, 436nm
- 1990's — Wafer scanners, 365nm, 248nm
- 2000's — 193nm, 157nm, EUV …

# So, why does scaling help?

INCREASED CHANCE OF A BALL DROPPING IN A POCKET

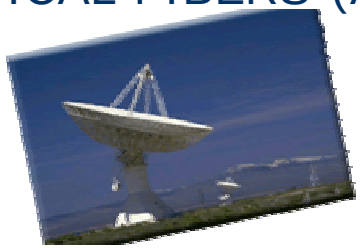
PROBABILITY → TENDS TO 1

- Imagine a billiards table where the balls were electrons and the pockets were holes
- As the table is shrunk the probability of the ball dropping in a pocket (an electron meeting a hole) increases.
- When the size of the table is the size of the pocket (my kind of billiard table) the chance → 1

**REDUCED SIZE GIVES ENHANCED LIGHT OUT**

# Impact of Scaling to Reduced Dimensions in Light Engines

- VOICE AND DATA ARE BEING CARRIED INCREASINGLY BY LASERS OVER OPTICAL FIBERS (AT THE EXPENSE OF SATELLITES)



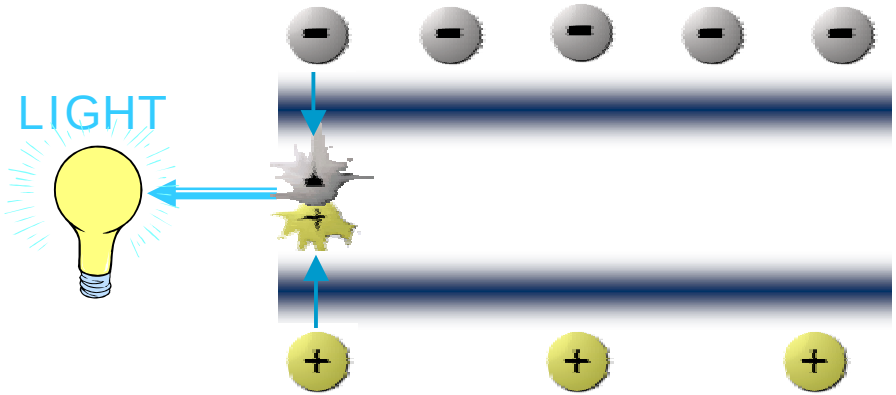
- LIGHT EMITTING DIODES ARE GETTING INCREASINGLY **BRIGHTER**, CHALLENGING CONVENTIONAL LIGHT BULBS FOR ILLUMINATION

- SHORT WAVELENGTH LASERS (CURRENTLY **RED** AND IN THE FUTURE **BLUE**) ARE MAKING STORAGE MORE DENSE AND MORE AFFORDABLE

# Why Does Scaling Help?
## (A Primer on Light Emission)

A SEMICONDUCTOR HAS TWO CHARGE CARRIERS

- AN ELECTRON (NEGATIVE CHARGE)
- A HOLE (POSITIVE CHARGE)




ELECTRONS

HOLES

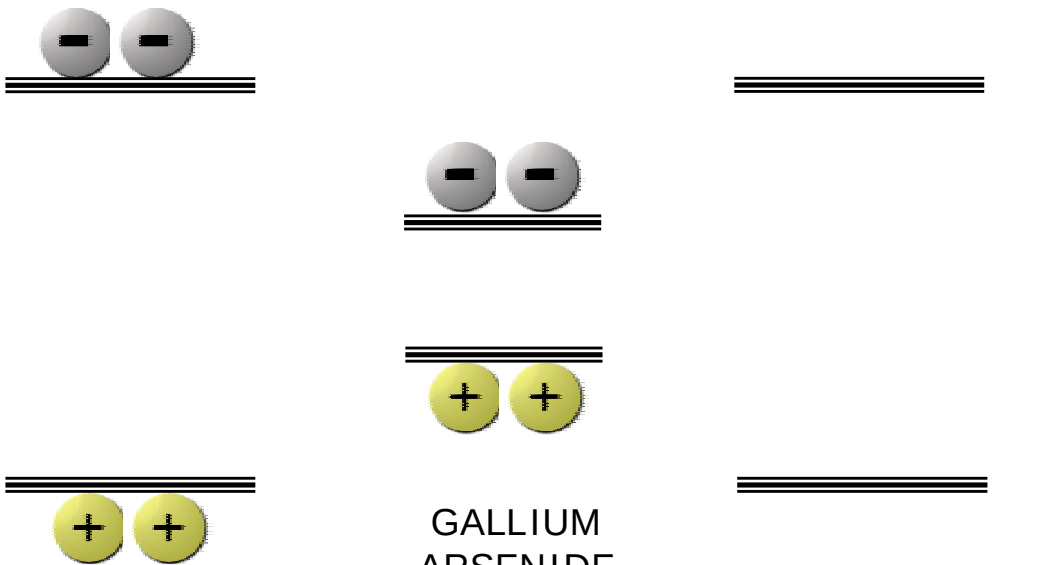
SEPARATED IN ENERGY BY AN AMOUNT CALLED THE BAND GAP

ELECTRONS AND HOLES ATTRACT EACH OTHER AND WHEN THEY MEET THEY ANNIHILATE EACH OTHER AND THE ENERGY IS RELEASED AS LIGHT

(THE RELEASE OF ENERGY BY ELECTRONS IS HOW X-RAYS ARE ALSO GENERATED)

# Scaling Lasers – Quantum Well Lasers

## MATERIALS WITH DIFFERENT BAND GAPS HAVE ELECTRONS (AND HOLES) AT DIFFERENT ENERGIES

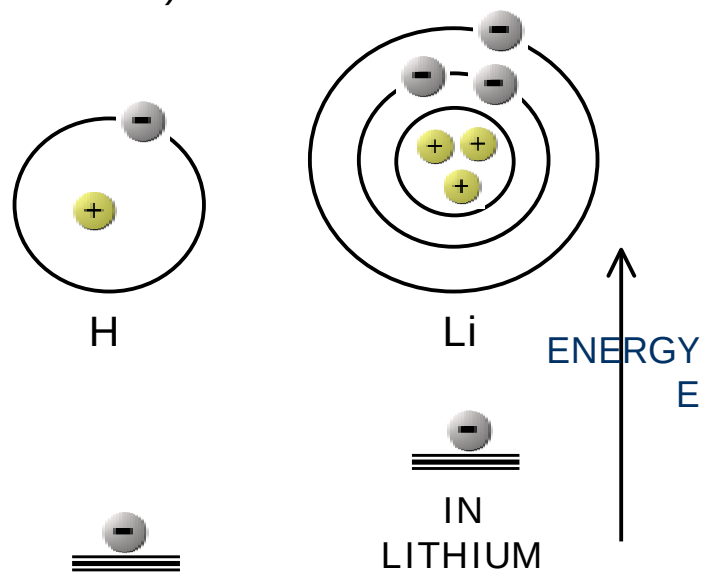


ALUMINUM GALLIUM ARSENIDE (AlGaAs)

GALLIUM ARSENIDE (GaAs)

ALUMINUM GALLIUM ARSENIDE (AlGaAs)

This is analogous to, say, electrons in the hydrogen atom (which has one electron) and lithium (which has three).

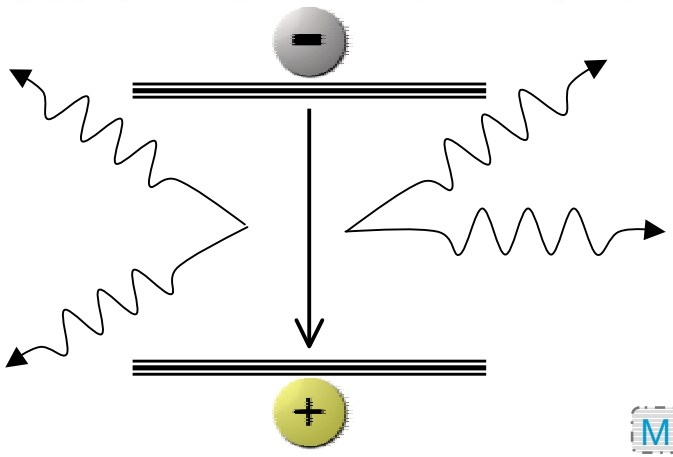


# Types of Light Engines

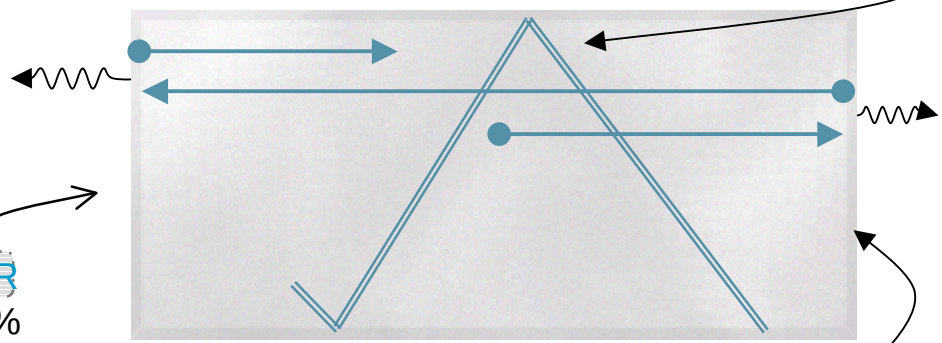
LIGHT EMITTING DIODES → LASERS

CURRENT IN

LIGHT OUT

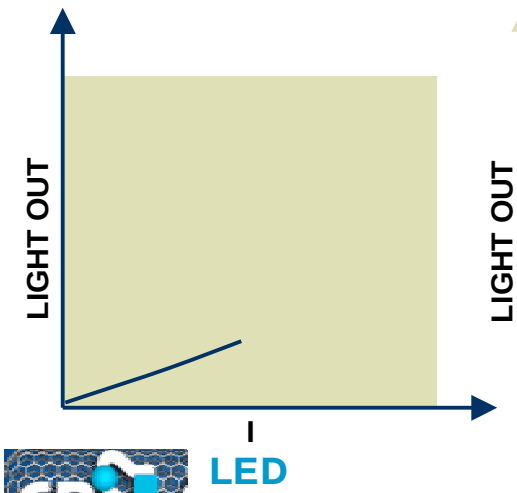


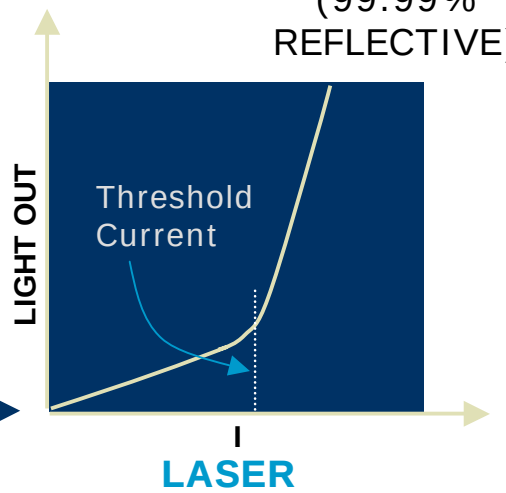
ALTERNATE PATHS OF EMISSION (AND FREQUENCIES) DIE BECAUSE THEY ARE NOT REINFORCED (NOT RESONANT)



MIRROR (99.99% REFLECTIVE)

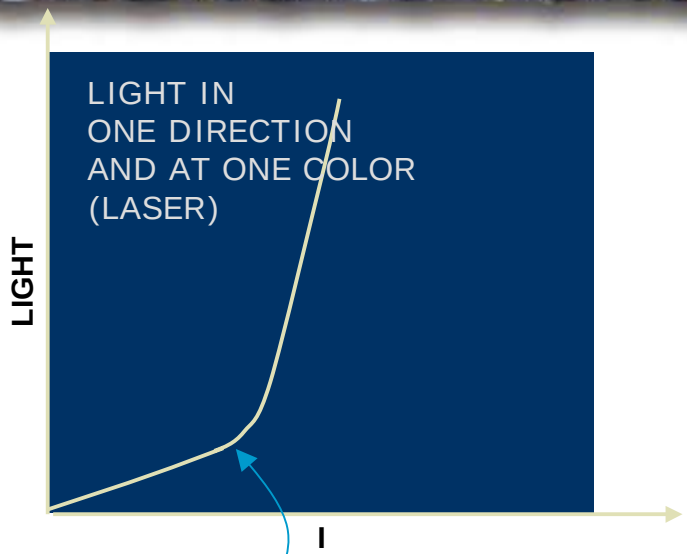
MIRROR

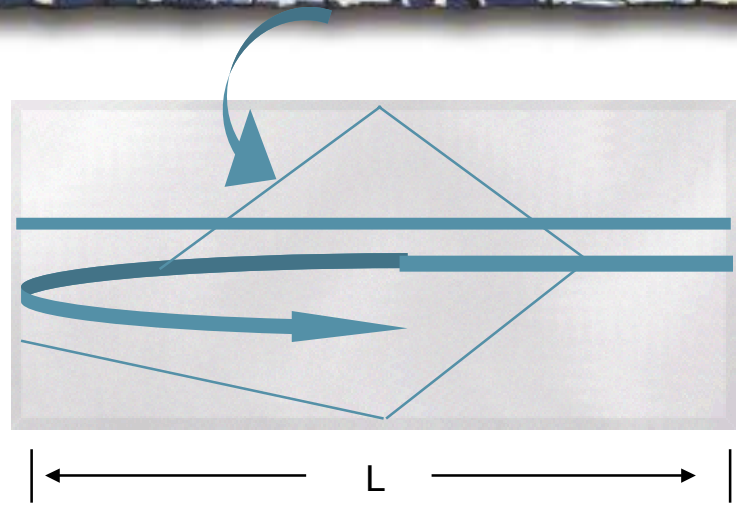



Light is generated within a cavity with mirrors. As the light bounces back and forth only the light reflected off the mirrors survives and one direction of light emission is selected. Also, much like a flute one tone (or color) is uniquely selected.

# Making the Laser Better by Shrinking the Cavity



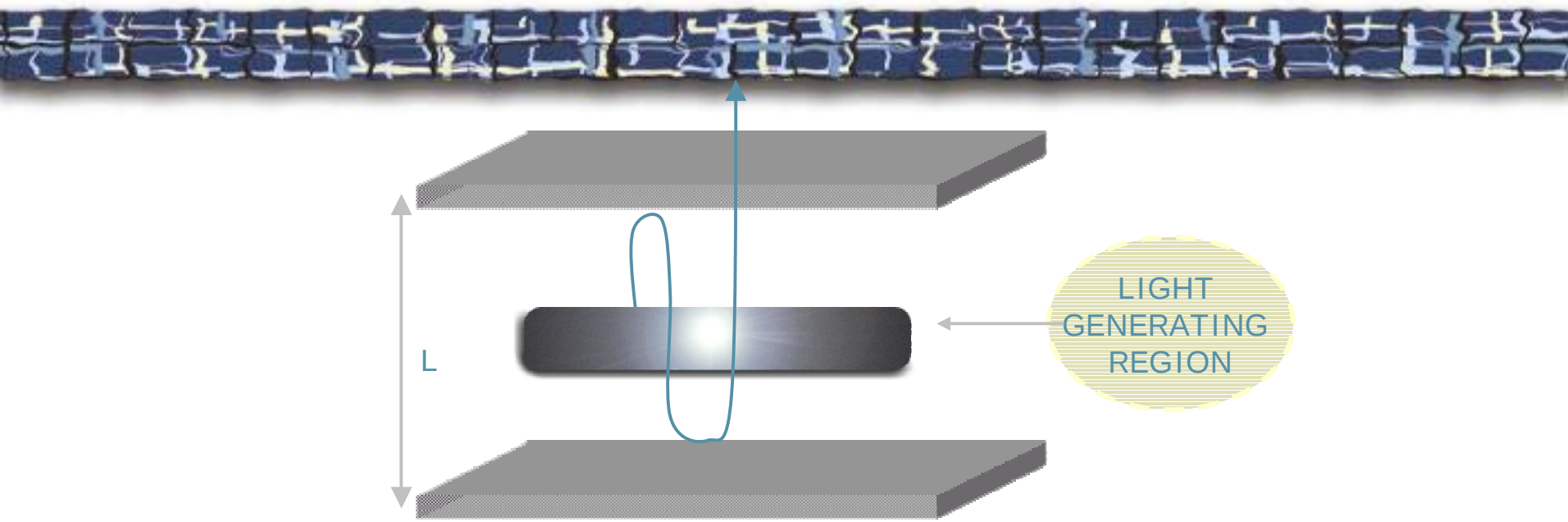

LIGHT IN ALL DIRECTIONS LIKE AN LED ⇒ REDUCES AS THE CAVITY SHRINKS ⇒ GOOD

⇓

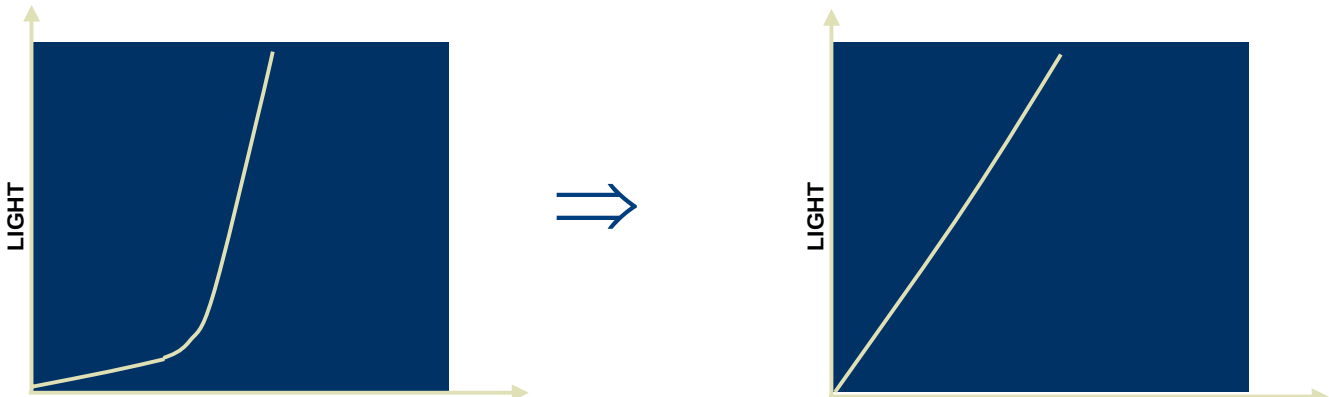
REDUCED CAVITY REDUCES THE LIGHT OUT ⇒ BAD

RESOLVE THIS WITH A VERTICAL CAVITY

# Vertical Cavity Surface Emitting Laser (VCSEL)



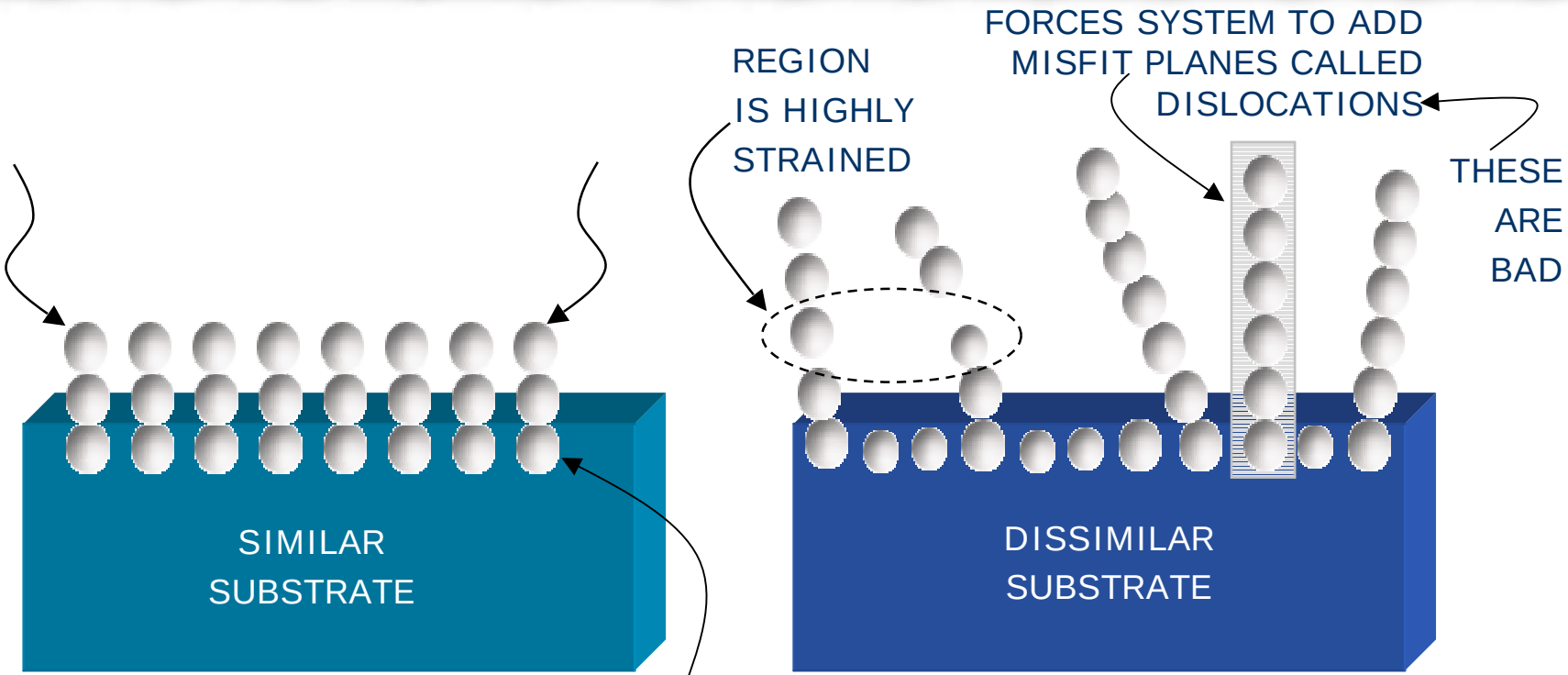

NOW THE CAVITY LENGTH L CAN BE REDUCED WITHOUT SACRIFICING LIGHT OUT




NORMAL LASER

IDEAL LASER

# The Problem with GaN
# No Substrate to Grow On




THE ATOMS OF THE SUBSTRATE PROVIDE A TEMPLATE TO GROW MATERIAL ON TOP, WITH THE GROWING ATOMS LINING UP WITH OR BONDING TO THE SUBSTRATE ATOMS HIS IS CALLED EPITAXY.

# A Family of Materials That Wants To Go NANO
## Gallium Nitride (GaN)

- GALLIUM NITRIDE HAS A VERY LARGE BAND GAP (3.4 Ev) WHICH ALLOWS IT TO SUSTAIN LARGE ELECTRIC FIELDS. IT WILL PROVIDE TECHNOLOGY FOR THE WIRELESS BASE STATIONS AND RADARs OF TOMORROW

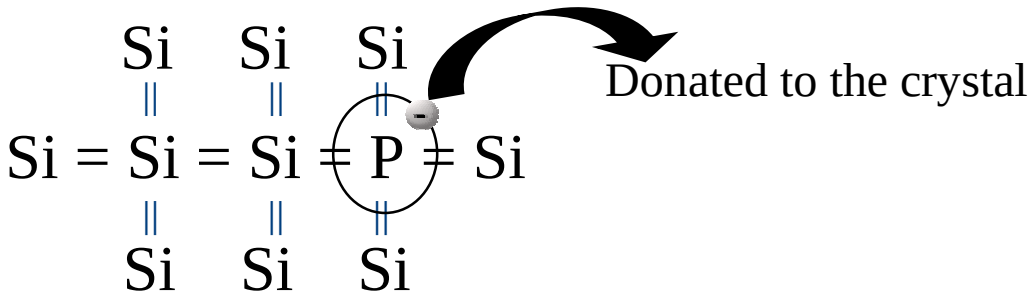
  (BUT THAT'S A DIFFERENT BORING TALK)

- GALLIUM NITRIDE WHEN MIXED WITH INDIUM AND ALUMINUM TO FORM A FAMILY OF MATERIALS INCLUDING: ALUMINUM GALLIUM NITRIDE (AlGaN) AND INDIUM GALLIUM NITRIDE (InGaN) CAN EMIT LIGHT ACROSS THE FULL VISIBLE SPECTRUM

  (THAT'S THE SUBJECT OF THIS BORING TALK)

# The Concept of Doping

- IF YOU WANT ELECTRONS YOU SUBSTITUTE A SILICON ATOM (WHICH HAS 4 AVAILABLE ELECTRONS) WITH, SAY PHOSPHOROUS (WHICH HAS 5 AVAILABLE ELECTRONS). THE EXTRA ELECTRON IS GIVEN TO THE CRYSTAL.




- MAXIMUM DOPING ALLOWED BY THE CRYSTAL IS REPLACING 1 IN 100 ATOMS.

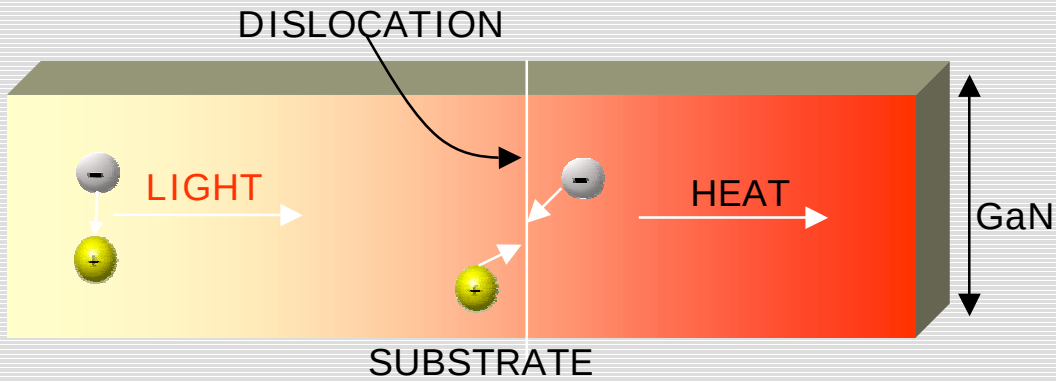
  THE NUMBER OF ATOMS IN Si IS $10^{22}/CM^3$.

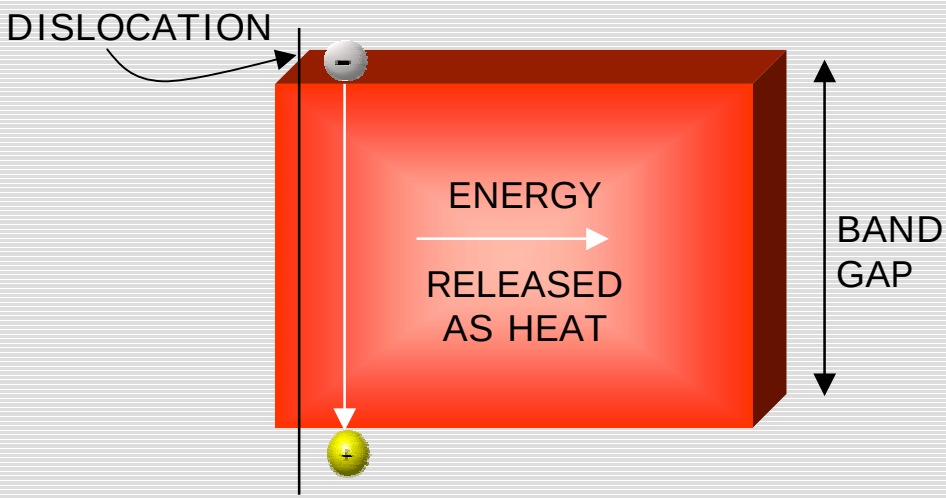
  THE NUMBER OF DOPANTS IS $10^{20}/CM^3$.

  THE DISTANCE BETWEEN DOPANTS IS 5NM TOO LARGE!

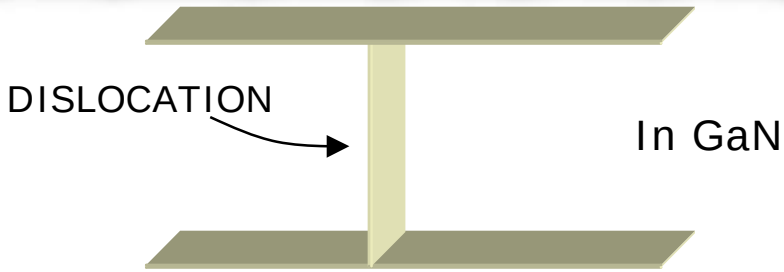
  WANT ELECTRONS TO BE NOT LIMITED BY NUMBER OF DOPANTS

# Dislocations are Non-Radiative Regions

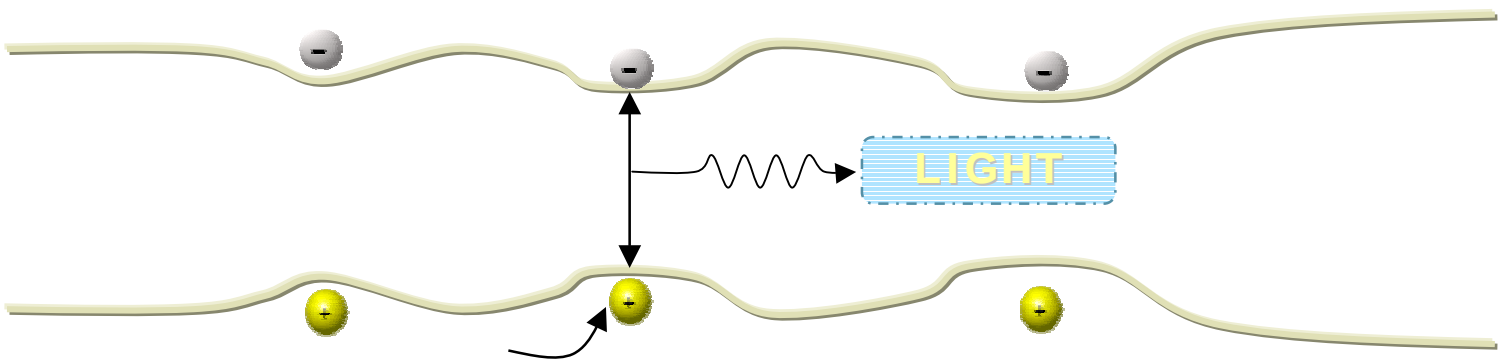


# Nature's Nanoscale Solution to the Problem

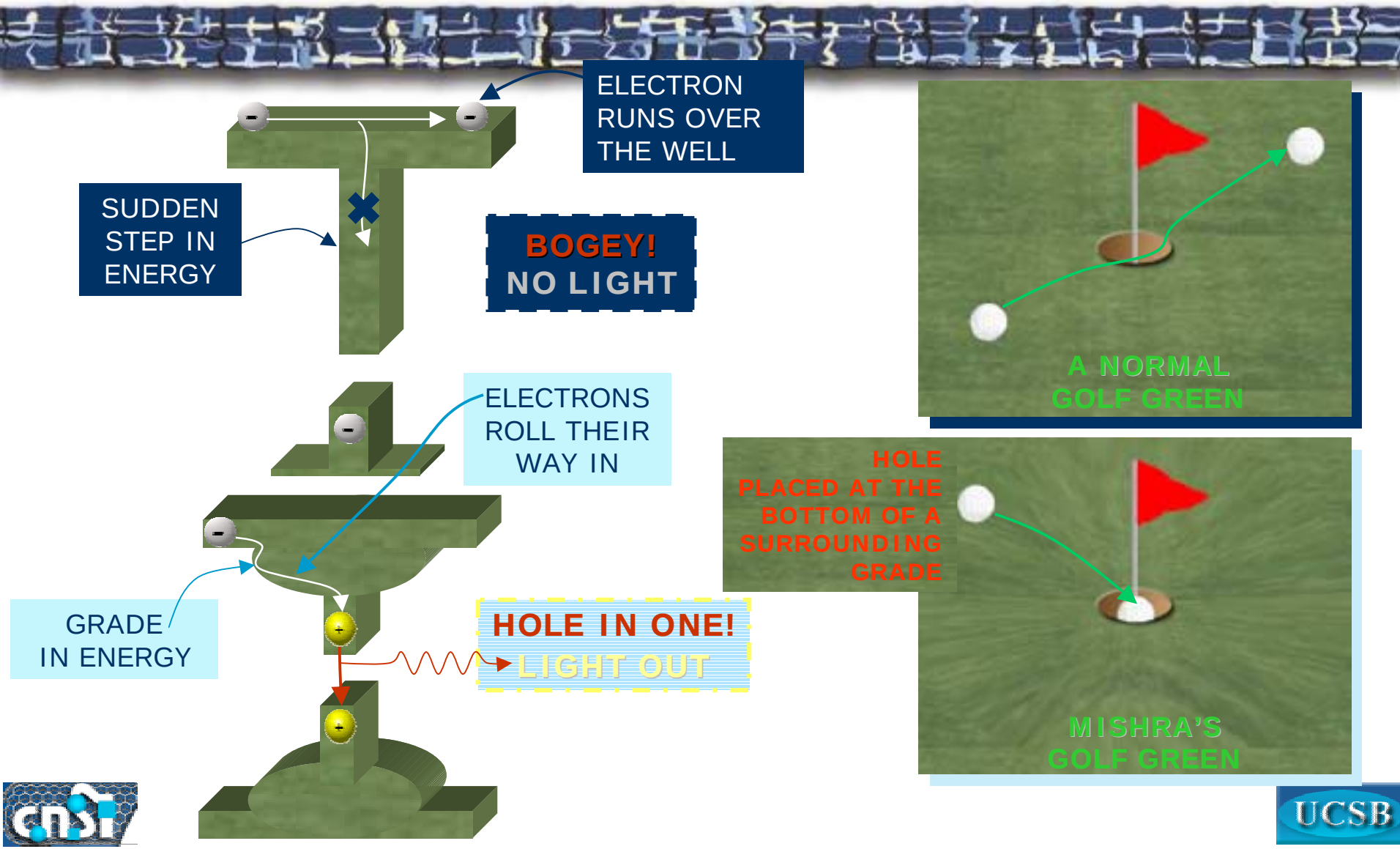



THE MATERIAL IS NOT UNIFORM; HAS FLUCTUATIONS

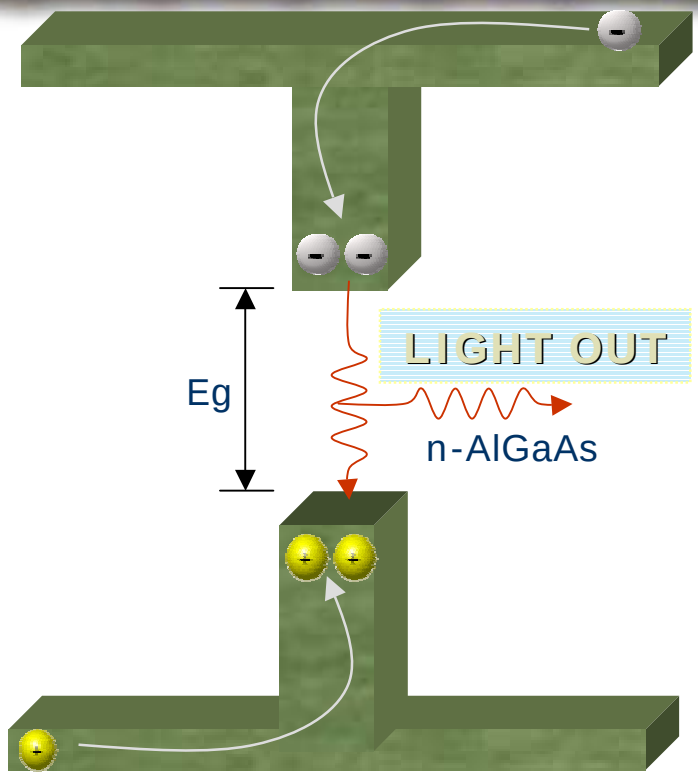


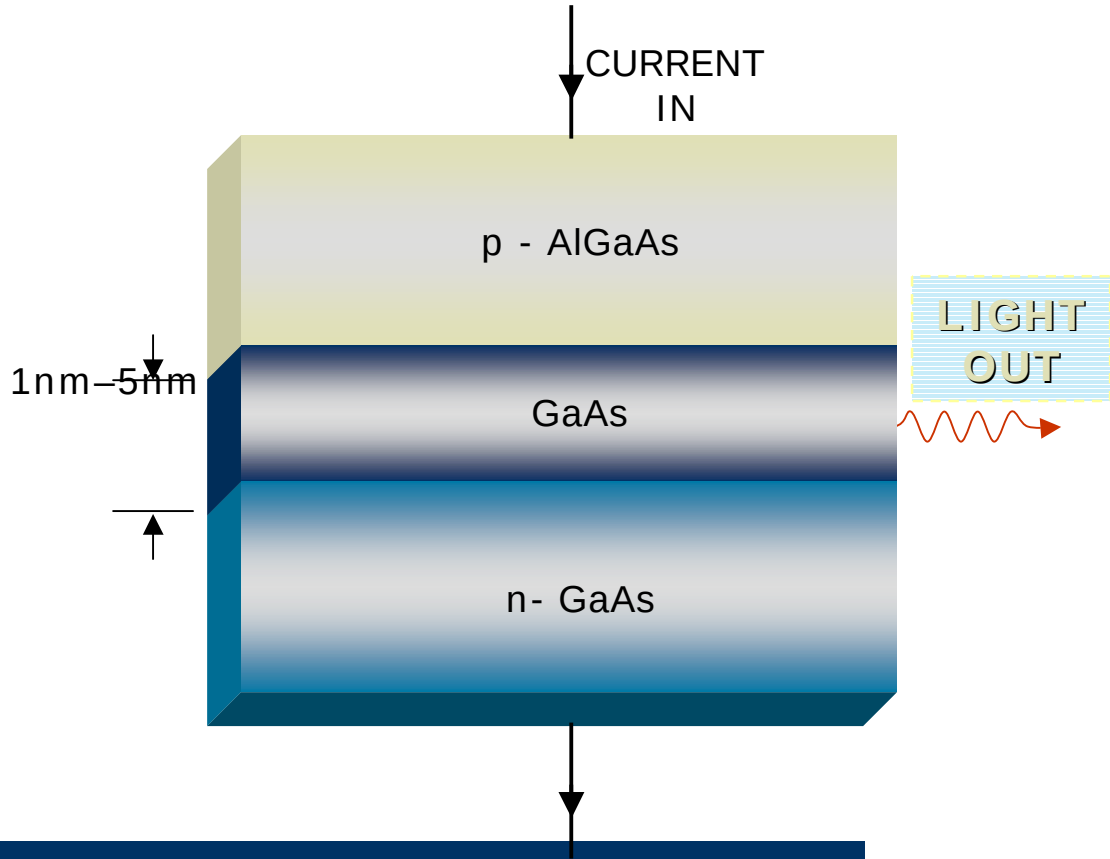

ELECTRONS AND HOLES COLLECT IN ENERGY WELLS DRAWN AWAY FROM DISLOCATIONS PRODUCING LIGHT NOT HEAT

# Need for Engineering New Solutions When You Shrink Dimensions



# Quantum Well Lasers




FREQUENCY (OR COLOR OF THE **LIGHT OUT** IS
PROPORTIONAL TO THE BAND GAP
(OR THE ENERGY RELEASED ON ELECTRON/HOLE ANNIHILATION)

# Let's Get Calibrated

- 1 CYCLE PER SECOND = 1 HERTZ = 1 Hz

Ac POWER: 60 Hz

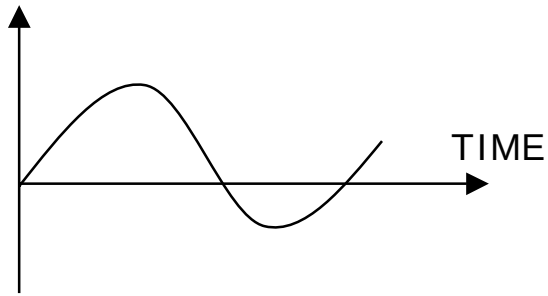
AUDIO FREQUENCIES: 20 Hz - 20,000 Hz

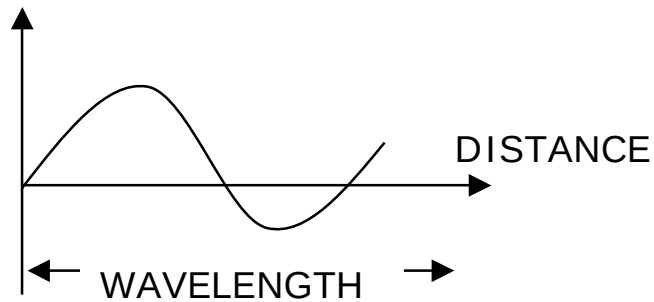
TELEPATHY: 400 Hz – 4000Hz

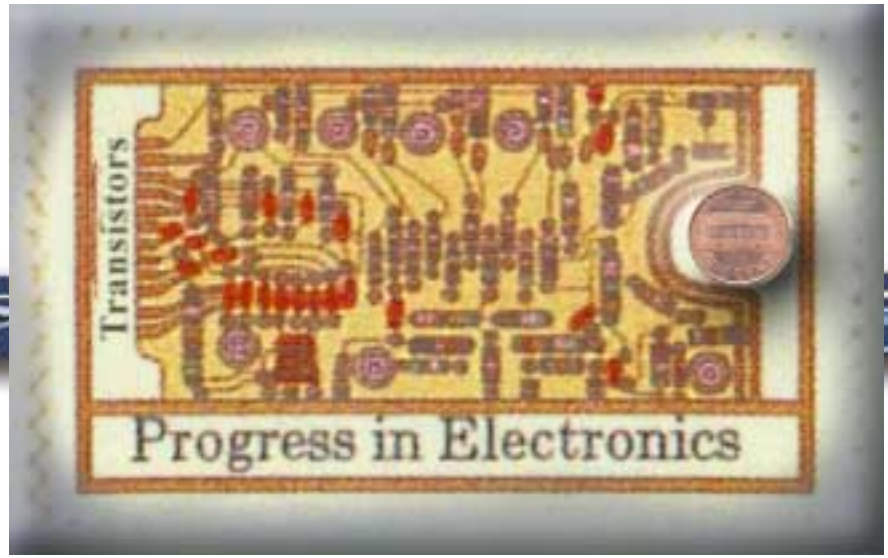
CELLULAR TELEPHONE: 900 MILLION Hz (900MHz)
- 2.4 BILLION Hz (2.4 GiGA Hz)

RADAR: 2 GHz – 94 GHz

OPTICAL COMMUNICATIONS: 300 TERA HERZ
300 TRILLION Hz
400 THz
500 THz
600 THz




# Summary

- SCALING DIMENSIONS HAVE LED TO ENHANCED PERFORMANCE AT A MUCH REDUCED COST
  - PENTIUM 4: 400 MILLION TRANSISTORS
    COST: $400
    BUYING 1000 TRANSISTORS FOR $.01


- NEW PRODUCTS KEEP EMERGING BECAUSE COMPUTING POWER IS NOW A COMMODITY; JUST ANOTHER PIECE IN YOUR LEGO SET
- AS DIMENSIONS SHRINK AND COMPLEXITY INCREASES, ACCESS (INPUT/OUTPUT) BECOMES A DOMINANT CONSIDERATION
- WE ARE NOW TRULY LIMITED BY OUR IMAGINATION (PLUS AS ALWAYS EXTENT OF SCIENTIFIC KNOWLEDGE AND MONEY).