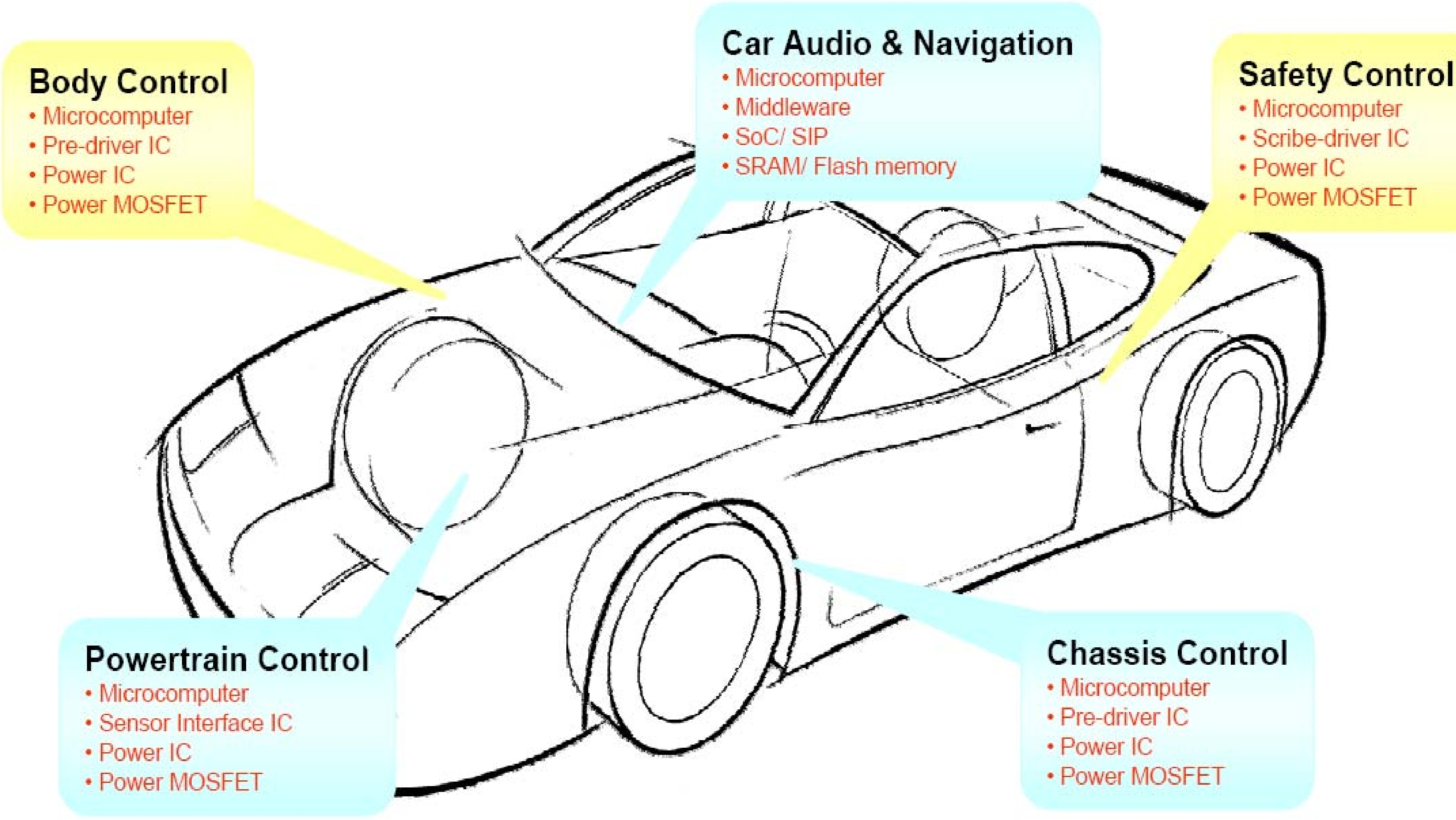
화합물 반도체 (I)
Introduction & Material Properties

2007 / 가을 학기

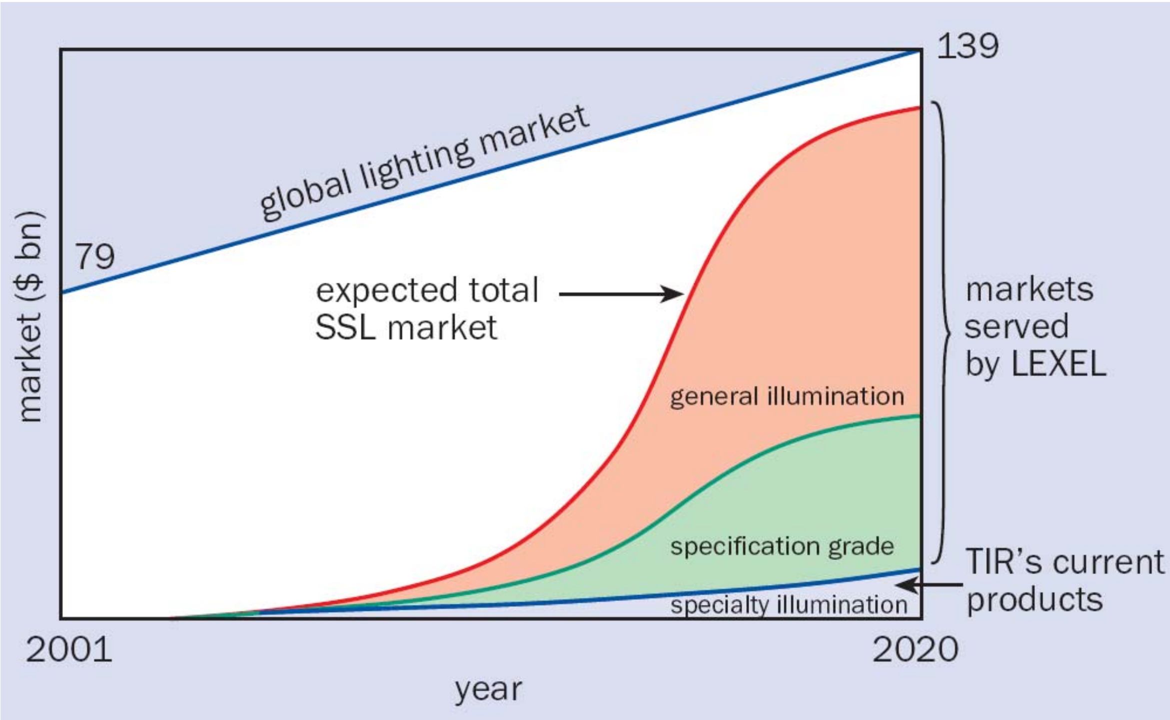
(주목할 분야 I) 자동차용 반도체

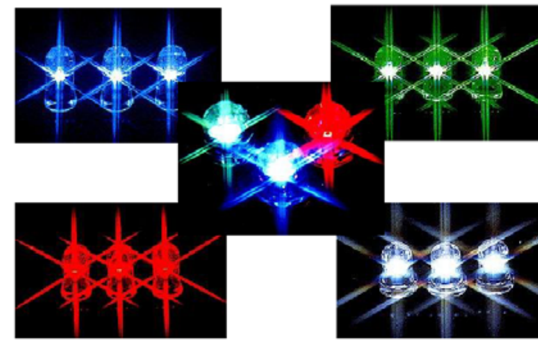


2015년 디지털 자동차

- **32/64-bit MPUs: 35 ~ 40개**
- **8/16-bit MCUs: 140-160개**

(주목할 분야 II) Solid-State Lighting

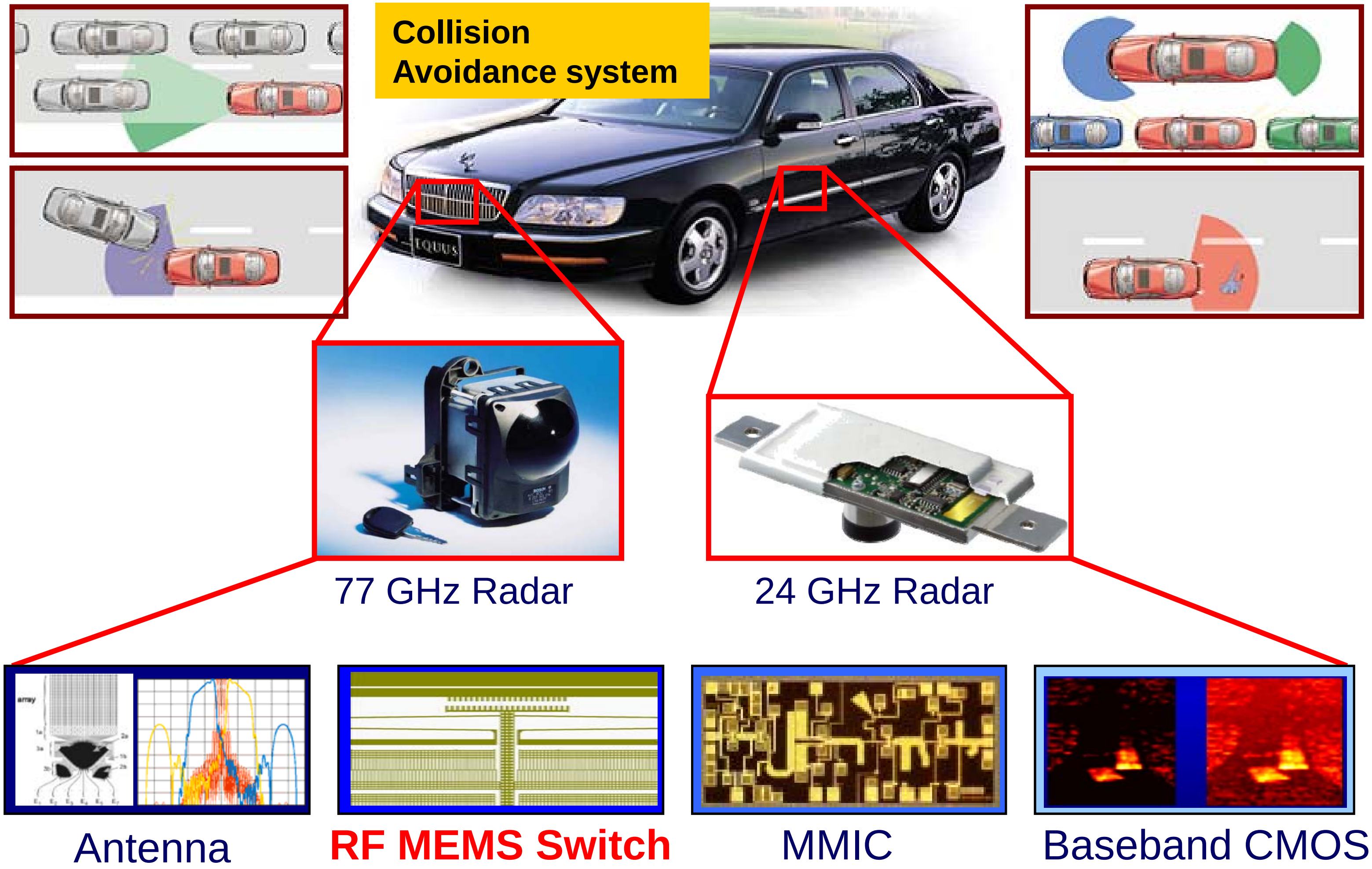




**Hyndai's LED
Front-Light**

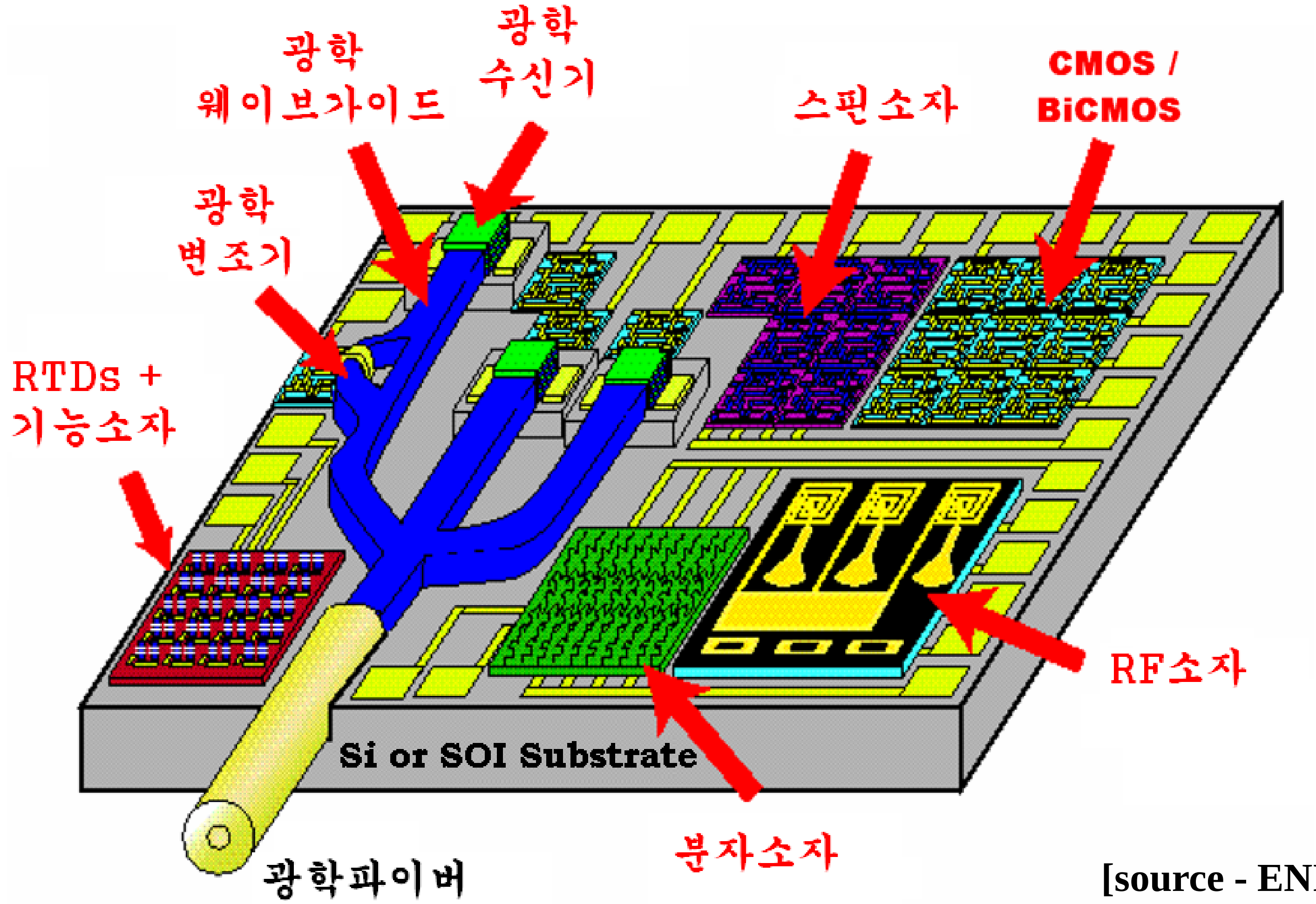
**Samsung's 46"
LED-based LCD TV**

(주목할 분야 III) Automobile Radar – System on Chip/Package



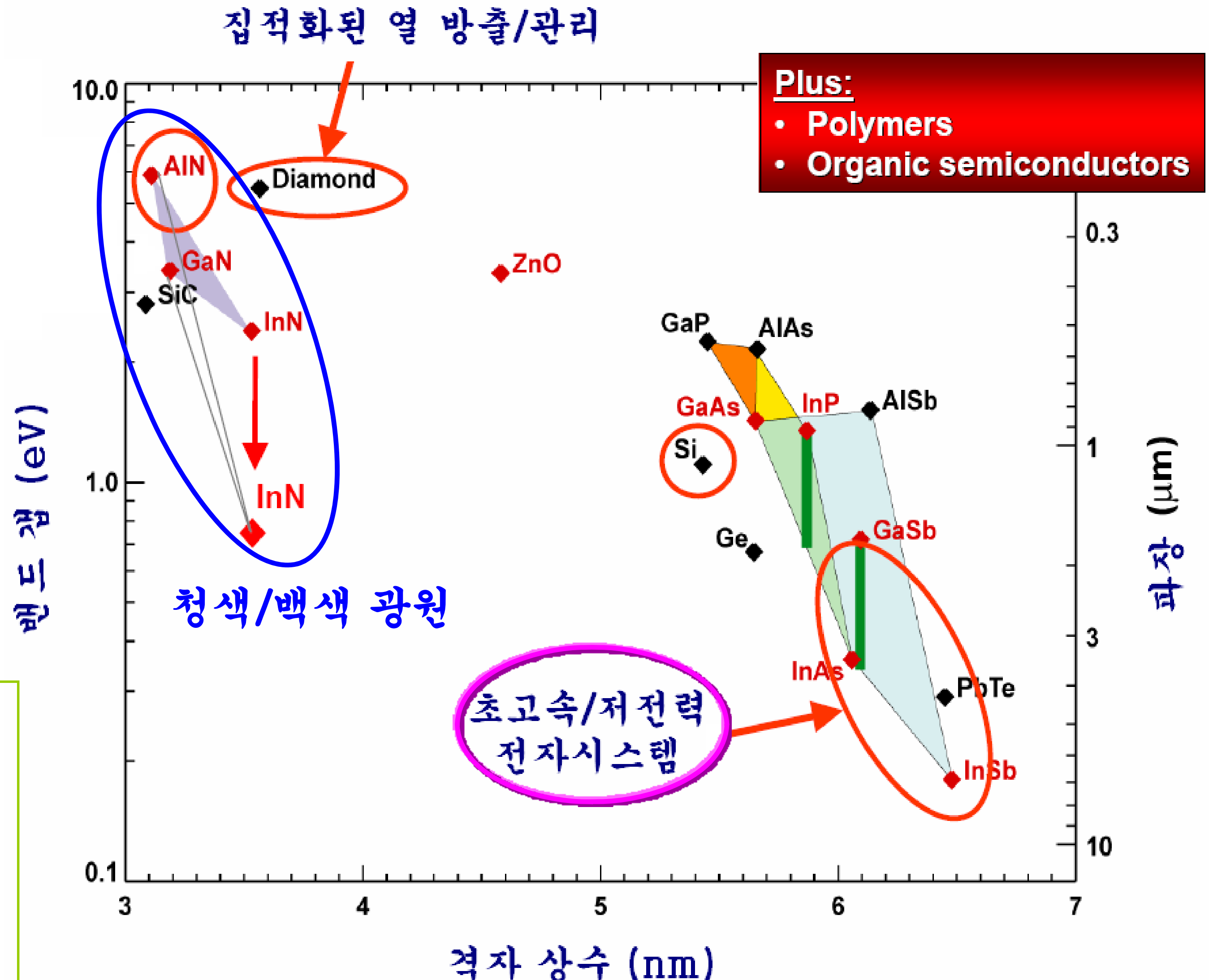
차세대 복합 반도체 시스템

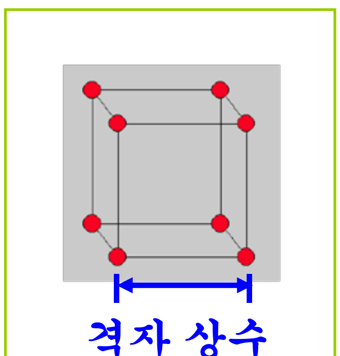
미래의 반도체 **chip** – 복합 기술들의 집적화



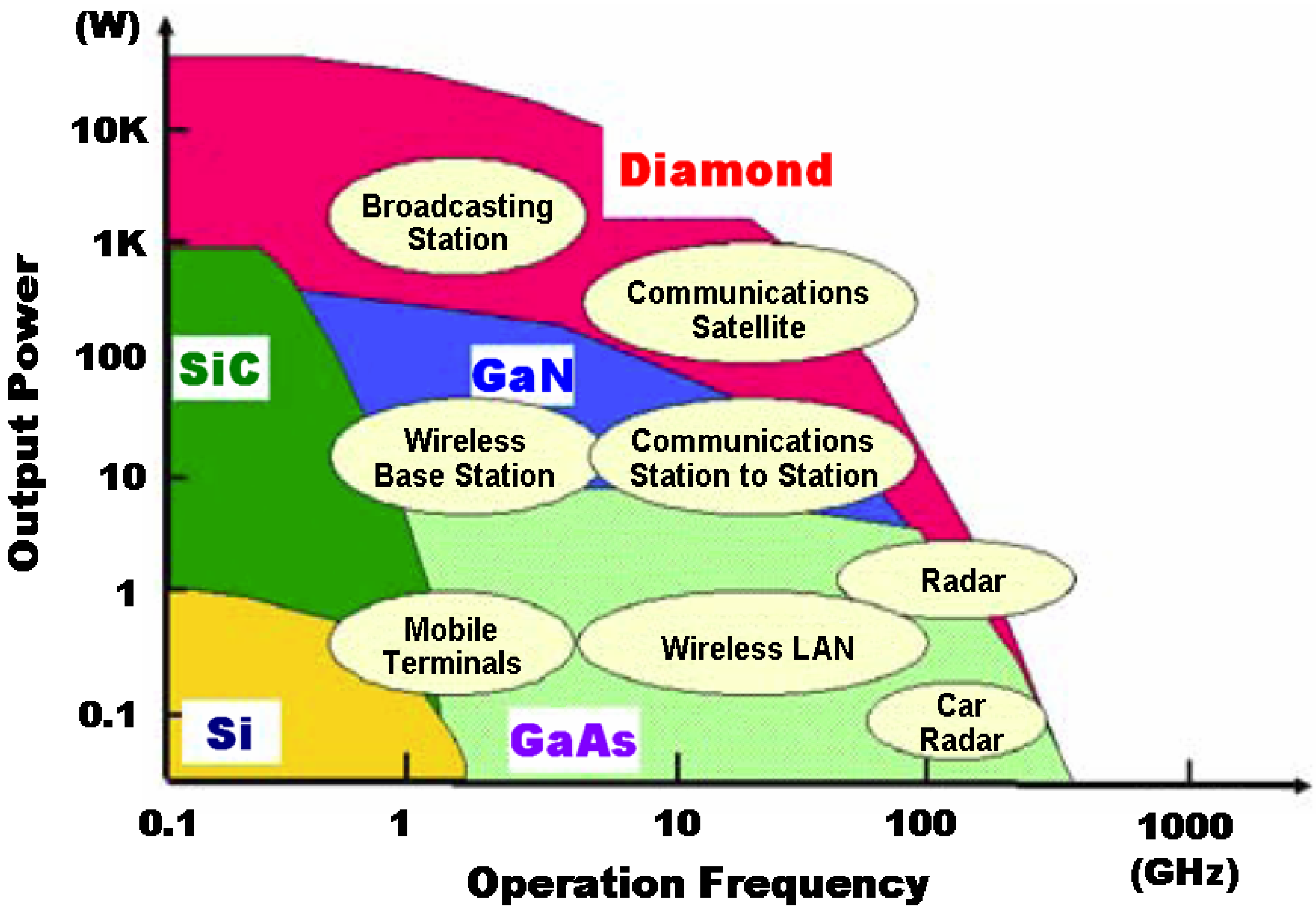
[source - ENIAC]

다양한 새로운 반도체 재료





초고주파 응용을 위한 반도체 종류



Compound Semiconductors

Table 1.2 Abbreviated Periodic Chart of the Elements.

II	III	IV	V	VI
4 Be	5 B	6 C	7 N	8 O
12 Mg	13 **Al**	14 **Si**	15 P	16 S
30 **Zn**	31 **Ga**	32 Ge	33 **As**	34 **Se**
48 Cd	49 In	50 Sn	51 Sb	52 Te
80 Hg	81 Tl	82 Pb	83 Bi	84 Po

Various Semiconductors

- Elementary : Si, Ge, C

(compound)

- III-V : GaAs, InP, InAs, InSb, GaP, ••••
- III-Nitride : GaN, AlN, InN
- II-VI : ZnO, ZnSe, HgTe, ZnS, CdS, ••••
- IV-VI : PdSe, PdTe
- Oxide (Semiconductor) : ZnO InZnO, GaZnO. ZnSnO, ••••

Wide Bandgap Materials

	Si	GaAs	GaP	3C-SiC	6H-SiC	Diamond	GaN
E_G (eV)	1.1 indirect	1.4 direct	2.3 indirect	2.2 indirect	2.9 indirect	5.5 direct	3.4 direct
Max. Operating Temperature	600	760	1250	1200	1580	1400	?
Physical stability	Good	Medium	Medium	Excelent	Excelent	Very good	Good
Thermal conductivity (W/cm)	1.5	0.5	0.8	5	5	10	1.3
μ_e (cm^2/Vs)	1400	8500	350	1000	600	2200	900
μ_h (cm^2/Vs)	600	400	100	40		1500	150
v_{sat} (10^7 cm/s)	1	2	-	2	2	2	2.7
Breakdown voltage (10^6 V/cm)	0.3	0.4	-	4		10	5
Dielectric constant	11.8	12.8	11.1	9.7		5.5	9

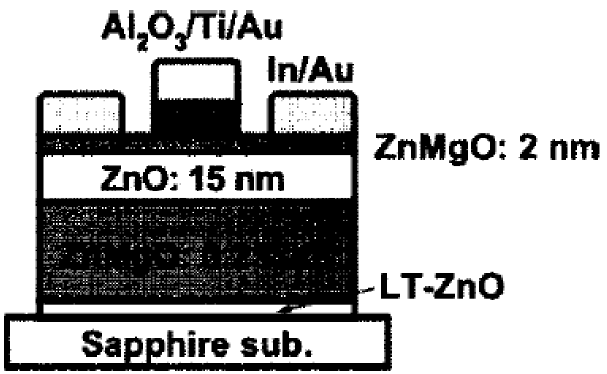
- ☺ Spectral selectivity
- ☺ Hardness
- ☺ Radiation resistance
- ☺ Stability at high temperature and pressure

- ☹ Crystal growth ⇒ Grain boundaries and dislocations
- ☹ Doping
- ☹ Contact technology

*** Oxide Semiconductors – ZnO (E_g=3.35eV)**

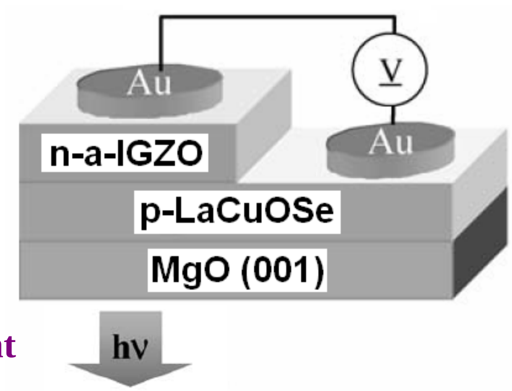
ZnO : Wide-bandgap Oxide Semiconductor

- **Why ZnO ?**
  - Wide and direct band gap (E_g = 3.4 eV at R.T.)
  - Large exciton binding energy : 59 meV
  - Band gap control by addition of Mg/Cd
  - Quantum structure (ZnO/ZnMgO) fabrications
  - Easy growth of high quality heterostructures
  - Low temperature growth
  - Challenges: accurate control of *n*- & *p*-doping
  - Fabrications of high performance devices (LEDs & FETs)

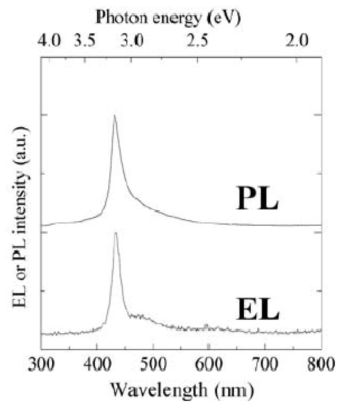


(Ref.) Appl. Phys. Lett. 89, 053502 2006

- **ZnO device applications**
  - Light emitting devices
  - Transparent electronic devices
  - Chemical and biological sensors



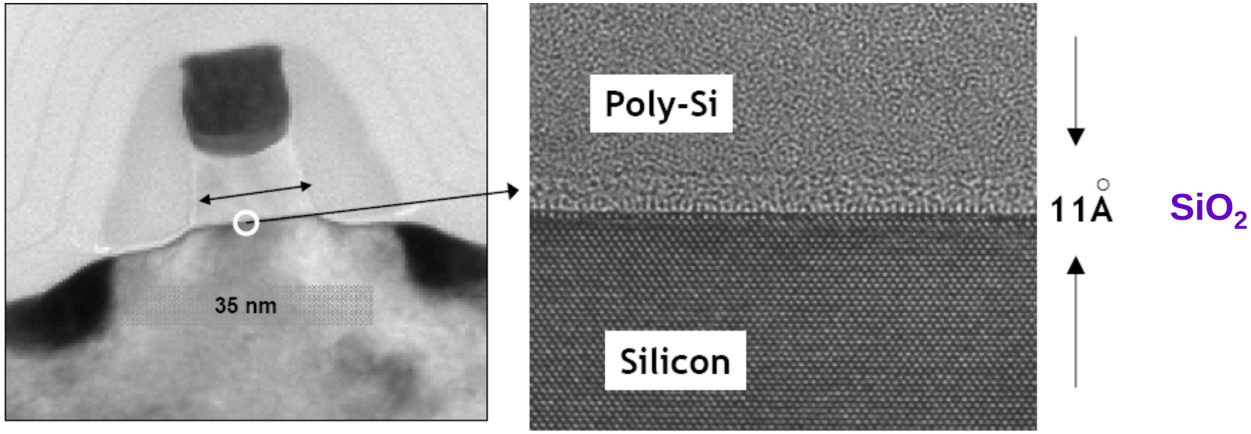
Transparent Blue LED



(Ref.) J. Electroceramics 17, 267–275, 2006

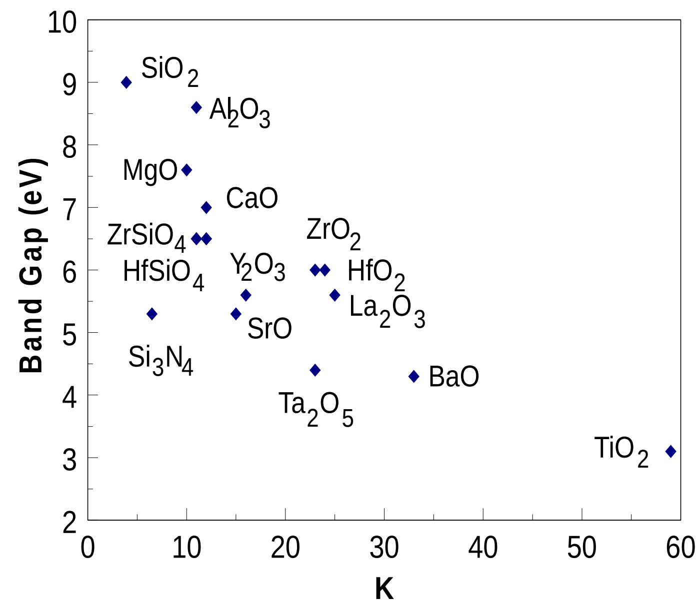
High-k Oxides (I)

35nm MOSFET (Intel)



Choice of High K Oxide for Si MOS

- High enough dielectric constant K
- Stable - no reaction with Si
  - Oxides with high heat of formation
  - Preferred – HfO_2, Zr, Y, La, Al
- Stable up to 1050°C
  - Low diffusion, amorphous $HfSiO_x$:N
- Band Offsets
  - Wide band gap
- Good interface
  - Few defects

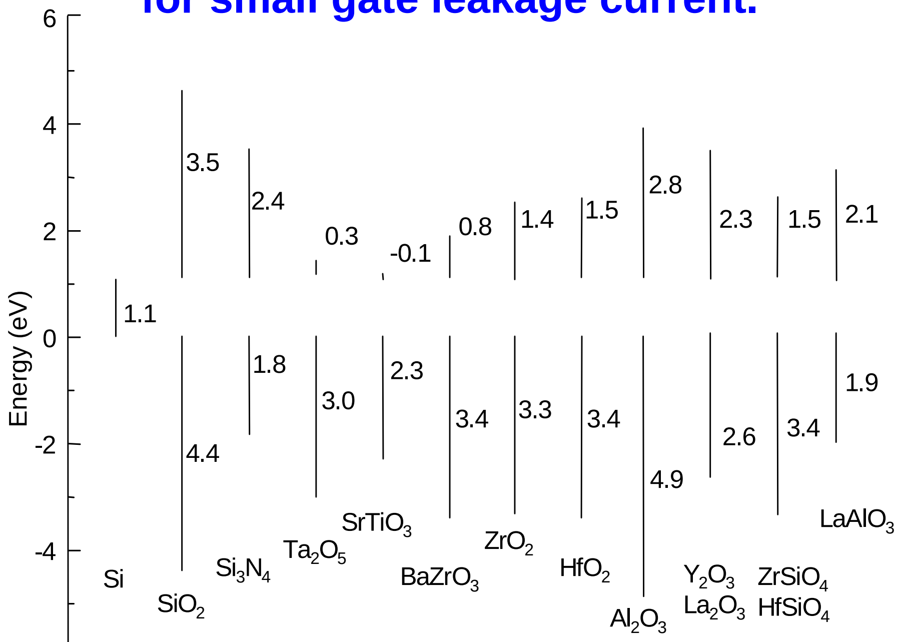


High K Oxide for MIM Capacitor

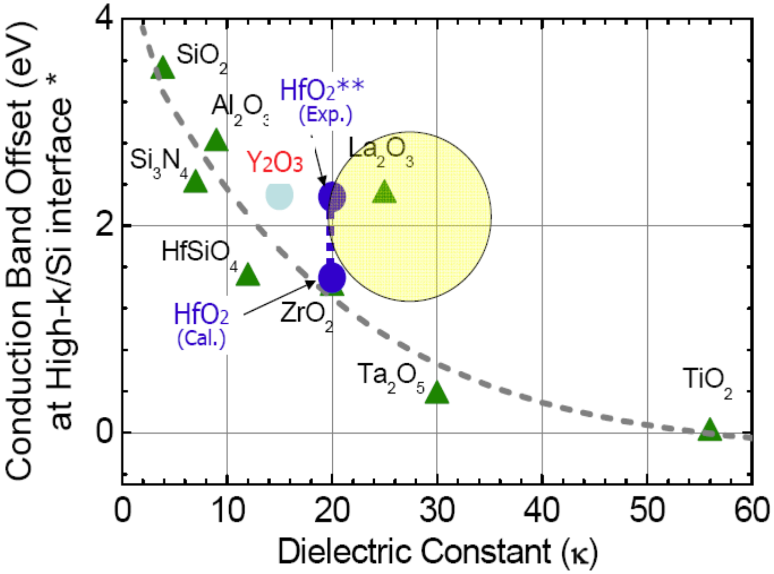
- $SrTiO_2$, BST for higher K

High-k Oxides (II)

*** Band offsets should be > 1 V for small gate leakage current.**



(Ref.) J. Robertson, 2006



World-Wide Compound Semiconductor Market

- Total Market for Compound Semiconductor Components :

18B $ at 2001 (78% - Optoelectronics)

*** Most Popular CS Materials**

- **GaAs – most common**
- **InP – high performance RF & 1.3/1.55μm optoelectronics**
- **GaN – new materials; blue/white LED & high power**

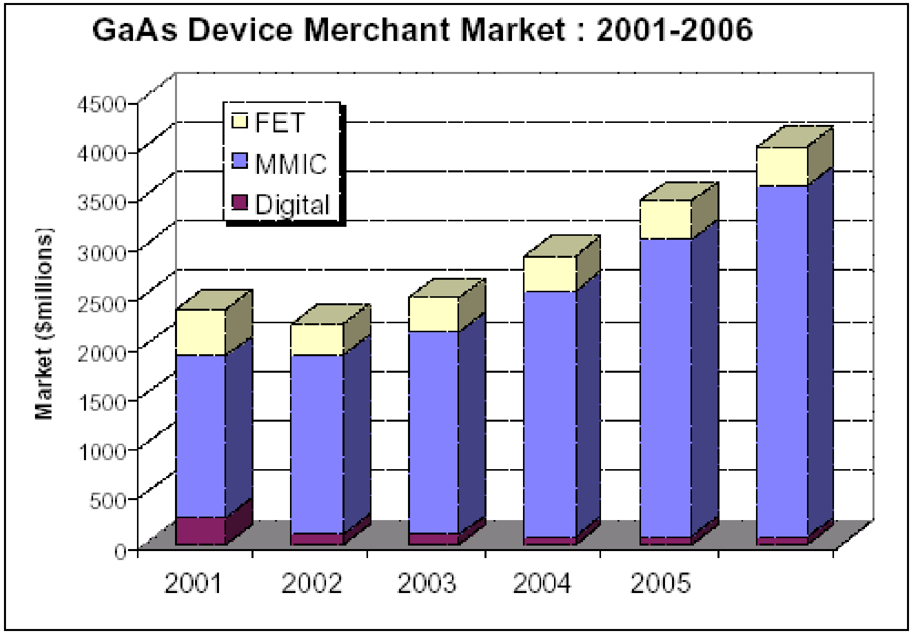
- Total LED Chip Market : 3.4B $ at 2003

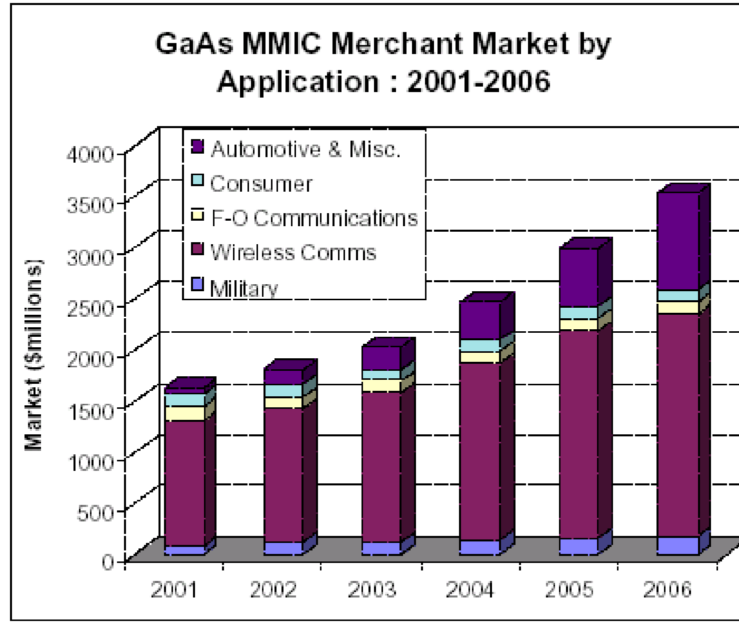
5B $ at 2007

Taiwan : more than 60% market

Highly Bright LED will dominate.

Worldwide GaAs Device & MMIC Merchant Market





	2006
Digital	79.8
MMIC	3532.1
FET	405.4
TOTAL	4017.3

	2006
Military	172.4
Wireless comms.	2168.9
F-O Communication	133.8
Consumer	119.1
Automotive & Misc.	937.9
TOTAL	3532.1

New Markets for III-V Electronic Devices

1. PA and Switch for Wireless LAN (5 GHz)

Wireless networking standards

Standard	Frequency band (GHz)	Data rate (Mbit/s)	Typical range (m)
IEEE 802.11b	2.4	11	100
IEEE 802.11g	2.4	54	50
IEEE 802.11a	5.0	54	20
Bluetooth	2.4	1–2	100

- 67% of the 177 million PAs in 2008 will be manufactured using GaAs
- All WLAN switch ICs will use GaAs technology.

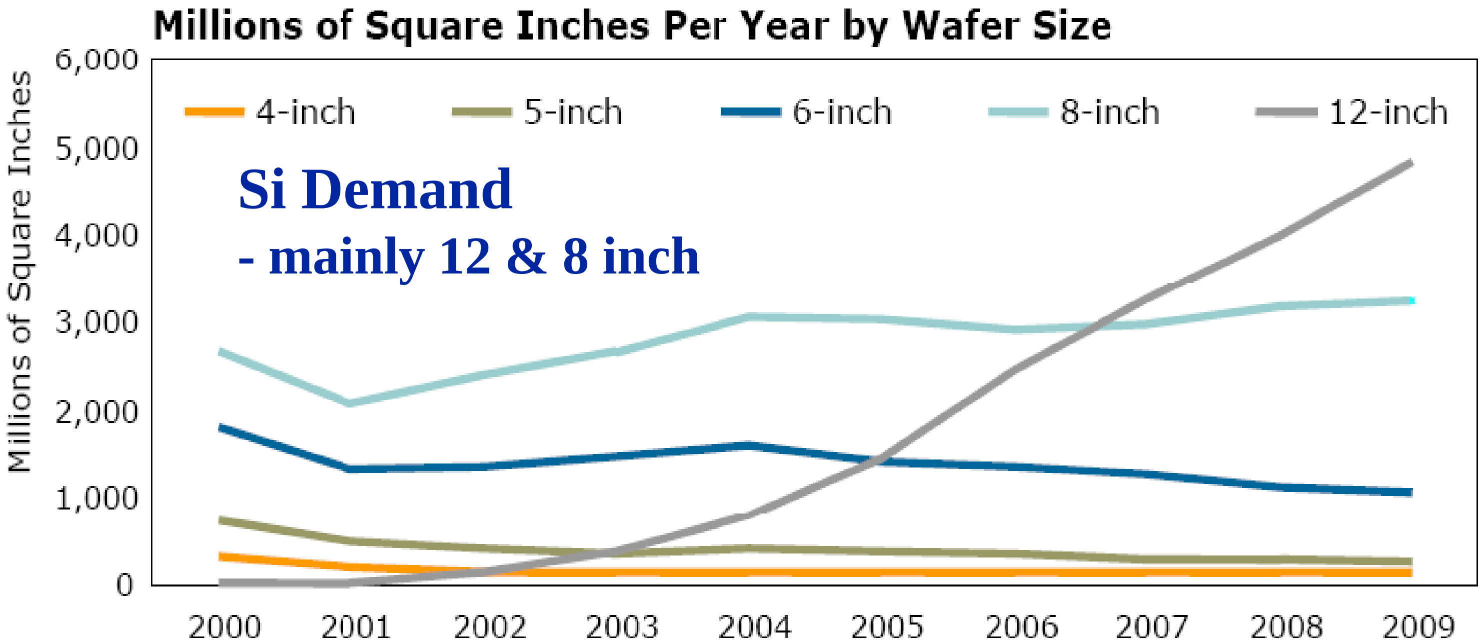
2. Automotive Radar (24 GHz and 77GHz)

- 5 million radar units in 2006 (Strategy Analytics)
- 100 million units in 2010 (?)

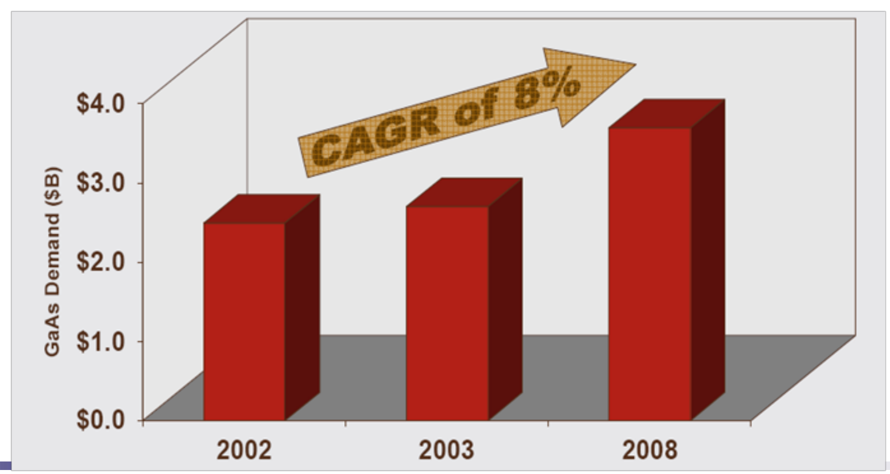
3. Satellite Communication Terminal

- release of 71-76, 81-86 and 92-95 GHz (70/80/90 GHz) bands

Global Wafer Demand – Si & GaAs



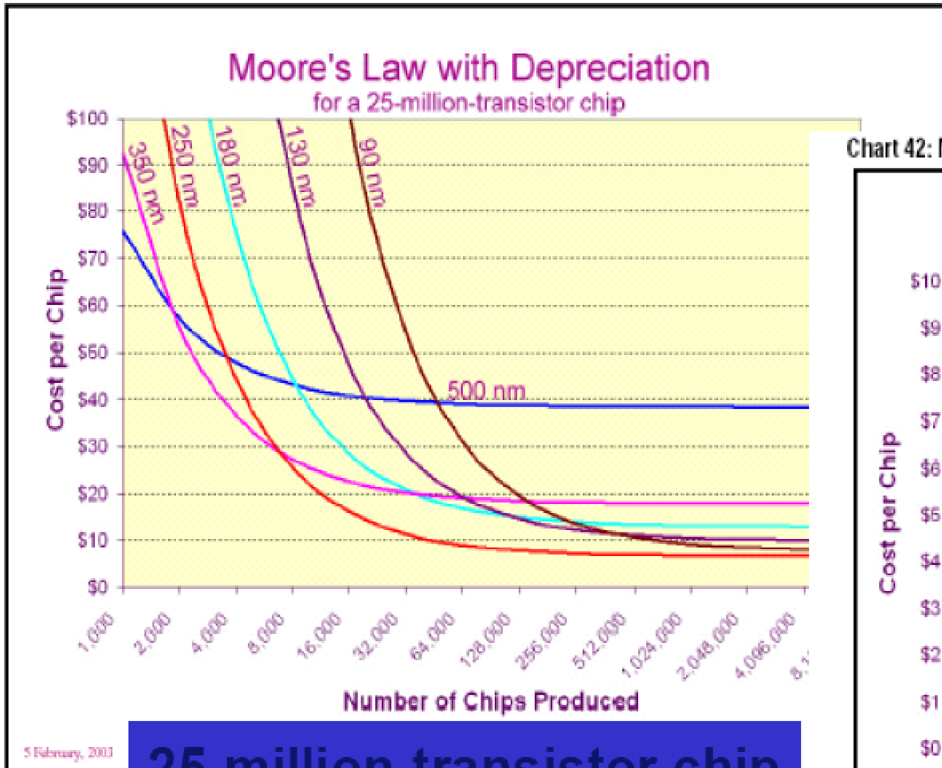
GaAs Demand
- mainly 6 & 4 inch



The Lowest Cost Technology ?

"not always the smallest dimension"

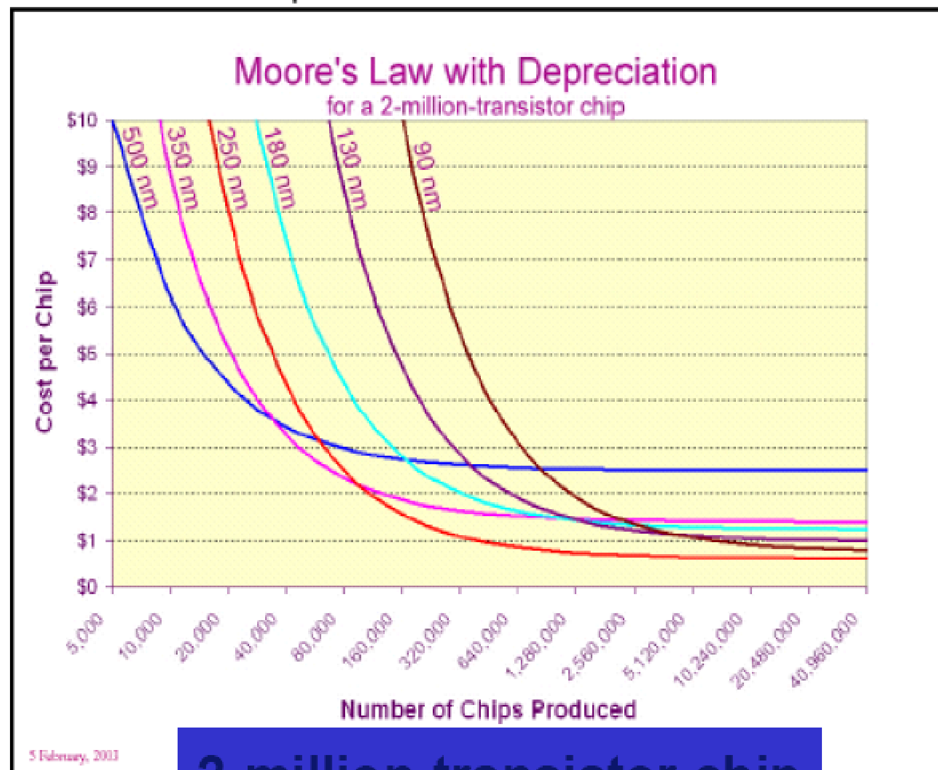
Chart 31: Moore's Law with Depreciation



Source: Nick Tred

25-million-transistor chip

Chart 42: Moore's Law with Depreciation



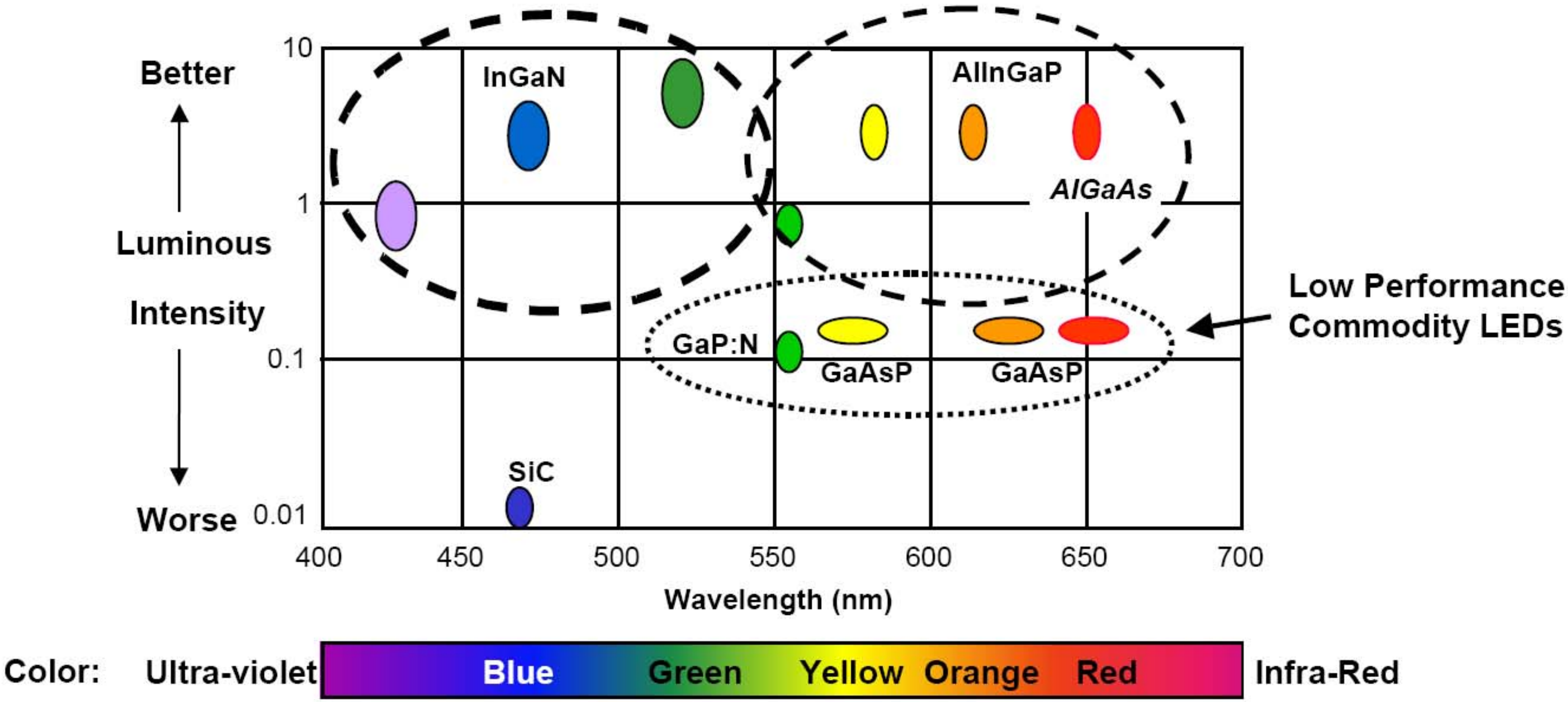
Source: Nick Tredennick

2-million-transistor chip

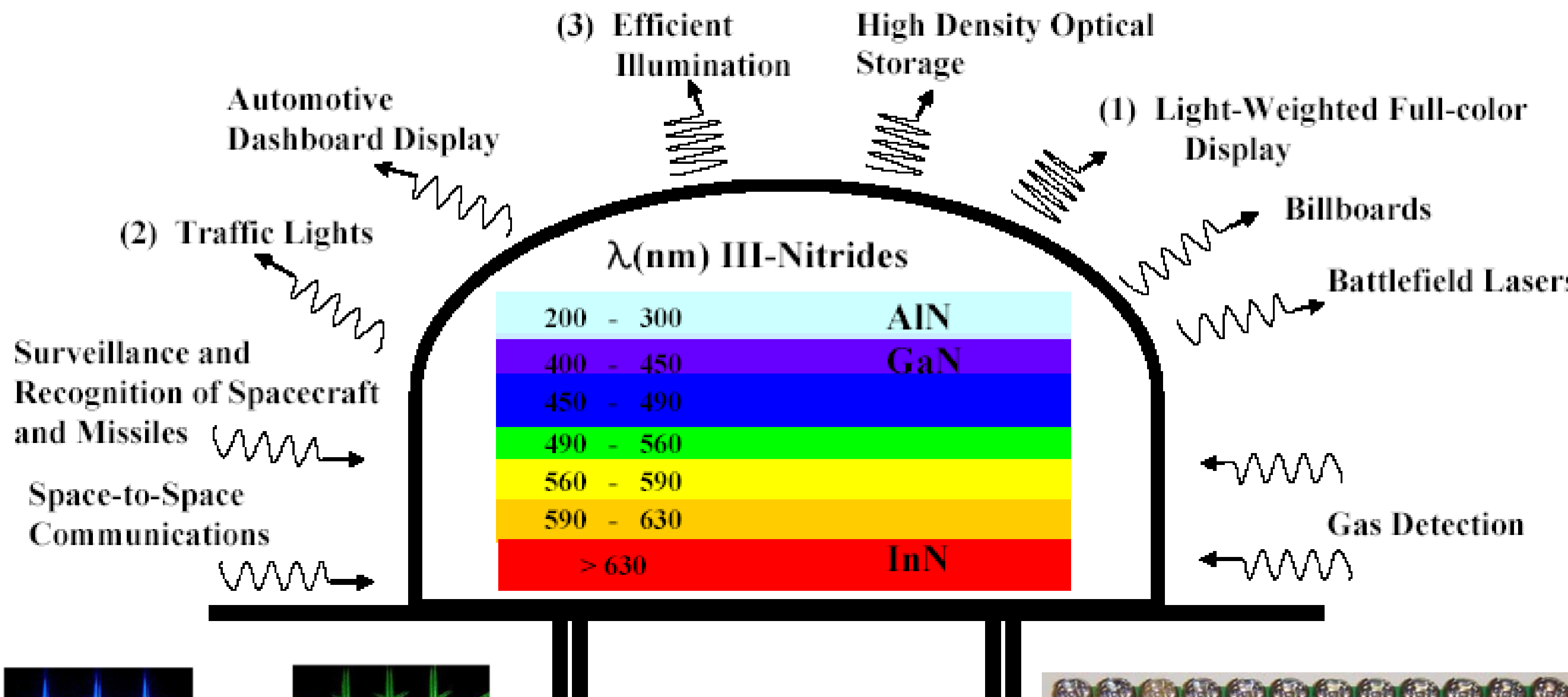
Source: Nick Tredennick

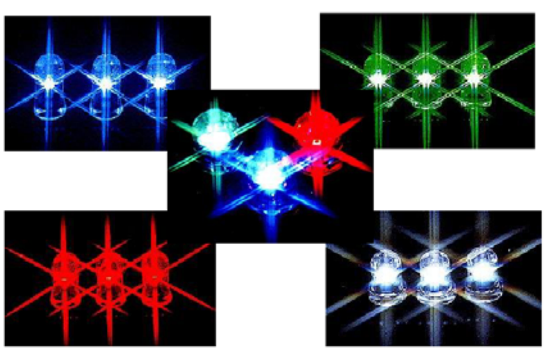
Editor of the *Dynamic Silicon Newsletter*,

Compound Semiconductors Materials for LEDs



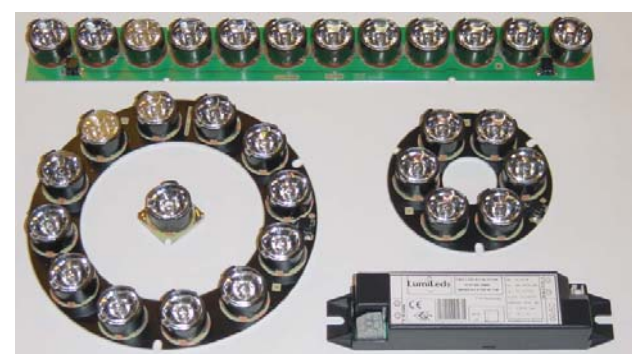
Applications of III-V Nitride Optical Devices



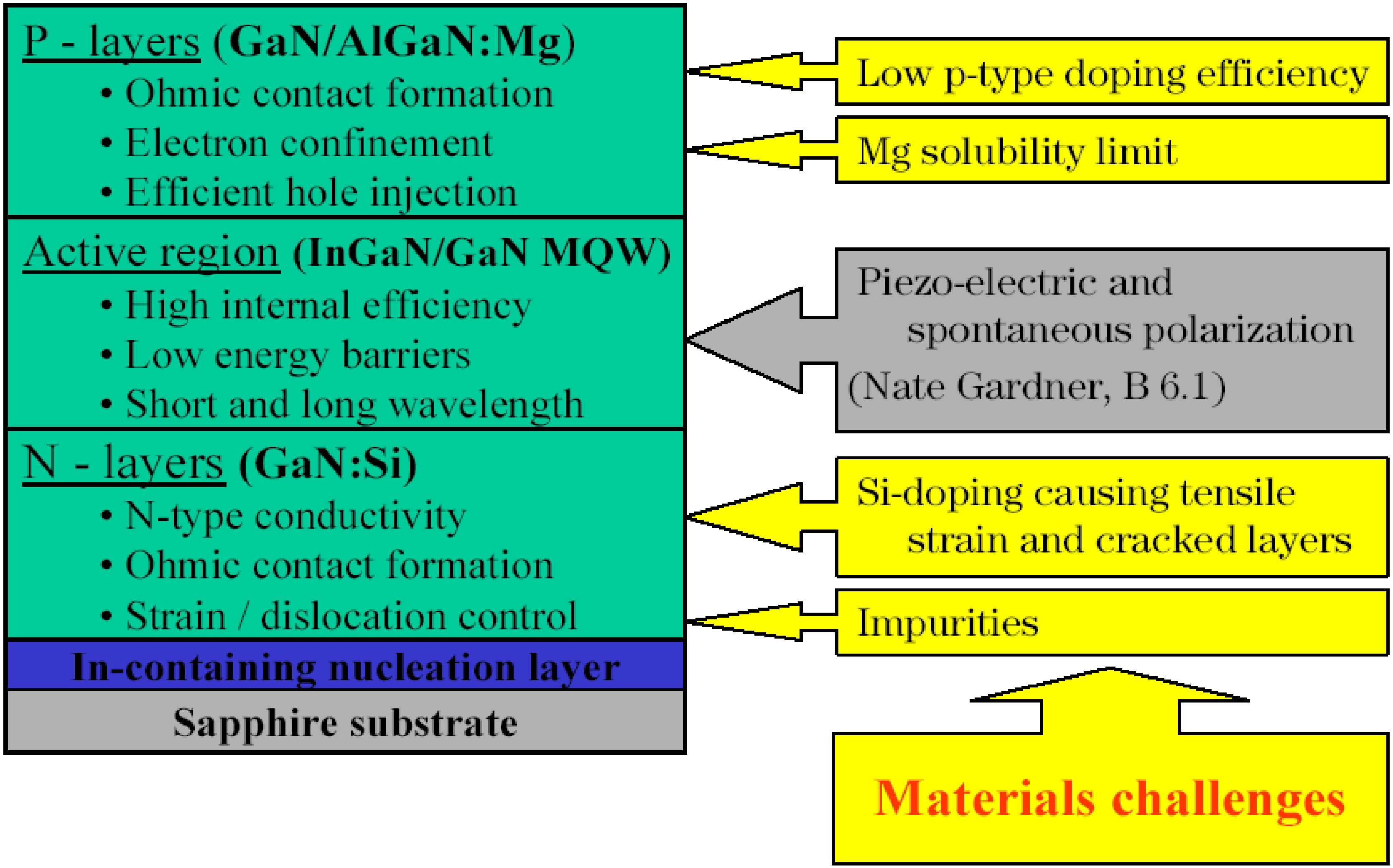


Major applications

(cellular phone, traffic light)



GaN LED Structures/Material Challenges



Various GaN Devices

Optoelectronic

- **LEDs**
  - Blue
  - Green
  - Violet
  - UV
  - White
- **LDs & VCSELs**
  - Blue
  - Violet
  - UV
- **Detectors**
  - UV photodetectors
  - Solar blind
  - High temperature
- **Others**
  - Acousto-optic modulator

➔ White LED (Sold-State Lighting)

Electronic

- **RF/Microwave**
  - power (HFETs,HEMTs)
  - Small signal(HFETs, HEMTs)
- **High power**
  - Thyristors, HBTs
  - Rectifiers
- **Power switches**
- **High voltage**
  - Rectifiers, Thyristors
- **High Temperature**
  - BJTs, HBTs
  - MOSFETs, MESFETs, HFETs
- **Piezoelectric sensors**
  - HFETs, SIS
- **Pyroelectric sensors**

➔ High Power (RF) Devices (Military)

Nichia's Blue LED with GaN & Shuji Nakamura

Timeline

- **Early 1990s** Nakamura and colleagues at Nichia report blue LEDs based on GaN.
- **December 1999** Nakamura leaves Nichia for the US, where he becomes a professor at UCSB and an advisor to Nichia's rival Cree.
- **December 2000** Nichia files lawsuit against Nakamura over alleged leaking of trade secrets.

- **August 2001** Nakamura launches damages claim for ¥2 billion ($19 million) against Nichia over blue LED invention.
- **September 2002** Tokyo court rules that although Nakamura does not own key patents, he is eligible for compensation.
- **February 2004** Tokyo district court awards Nakamura $189 million; Nichia appeals.
- **January 2005** Nakamura and Nichia agree to settle for $8 million at Tokyo high court.

*** Big Five in Blue & White LED**

- Nichia, Toyoda Gosei (Japan)

- Cree, Lumiled (USA)

- Osram (Germany)

USA's GaN Electronic Device Program (I)

Table 1. DARPA's three-track attack

Track/module type	*Prime contractor*	*Funding (Phase II)*	*Required module output power*	*Companies also on team*
1: X-band transmit/receive module	Raytheon	$26.9 million (up to $59.4 million)	60 W continuous wave	Cree
2: Q-band high-power amplifier module (more than 40 GHz)	Northrop Grumman Space Technologies	$16.5 million (up to $53.4 million)	20 W continuous wave	Monolithics, Emcore, Boeing, Sirenza Micro Devices
3: Wideband high-power amplifier module (2–20 GHz)	TriQuint Semiconductor	$15.8 million (up to $31.7 million)	100 W continuous wave	BAE Systems, Lockheed-Martin, II-VI, Nitronex, Emcore

Taken from DARPA's broad agency announcement

- launched from 2005
- supported by DARPA
(from Compound Semiconductor(CS) magazine, May 2005)
http://compoundsemiconductor.net/articles/magazine

USA's GaN Electronic Device Program (II)

Table 2. DARPA's 18 and 30 month "go/no-go" targets

Target	Track 1	Track 2	Track 3
18 months	8–12 GHz transistor with a 1.25 mm gate periphery operating at 40 V with 39 dBm continuous-wave output power, 12 dB gain, a PAE of 60%, a wafer yield of 50% and 10^5 hours' projected performance	Q-band transistor with a 0.5 mm gate periphery operating at 25 V with 39 dBm continuous-wave output power, 8 dB gain, a PAE of 35%, a wafer yield of 50% 10^5 hours' projected performance	As for Track 1
30 months	8–12 GHz power-amplifier MMIC operating at 48 V with 15 W continuous-wave output power, 16 dB gain, a PAE of 55% and a wafer yield of 50%	Q-band MMIC operating at 28 V with 4 W continuous-wave output power, 7.5 dB gain, a PAE of 37% and a wafer yield of 50%	2–20 GHz power-amplifier MMIC operating across a decade of bandwidth at 48 V with 15 W continuous-wave output power, 16 dB gain, a PAE of 30%, and a wafer yield of 50% (at least 12 three-inch wafers)

Taken from DARPA's broad agency announcement – actual program goals have been modified slightly

(from Compound Semiconductor(CS) magazine, May 2005)
http://compoundsemiconductor.net/articles/magazine