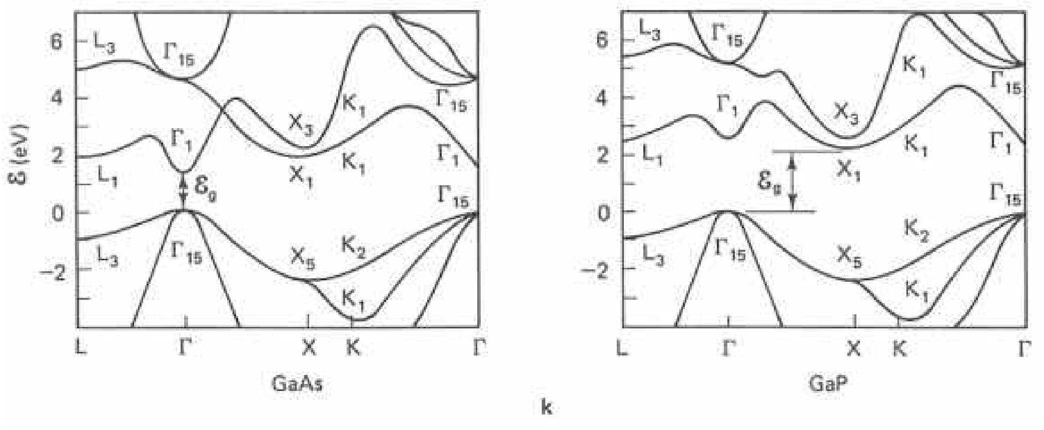
Chap 21 Optical properties of semiconductors

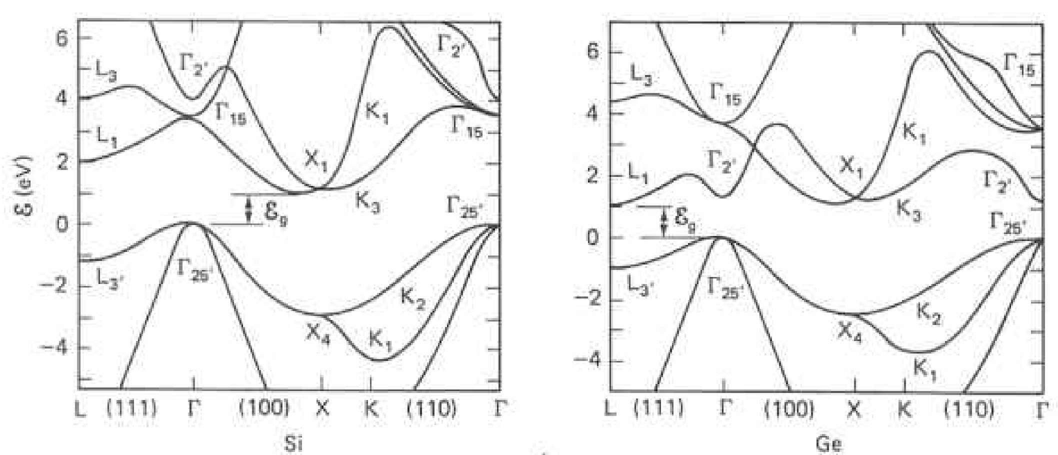
- cyclotron resonance
- direct and indirect optical transitions
- LEDs
- lasers
- solar cells

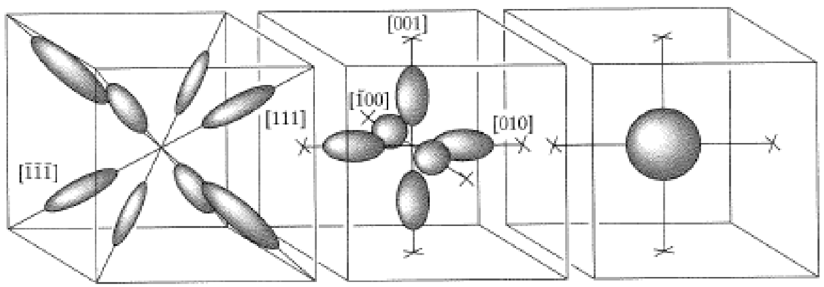
Dept of Phys

M.C. Chang

Band structures and Fermi surfaces

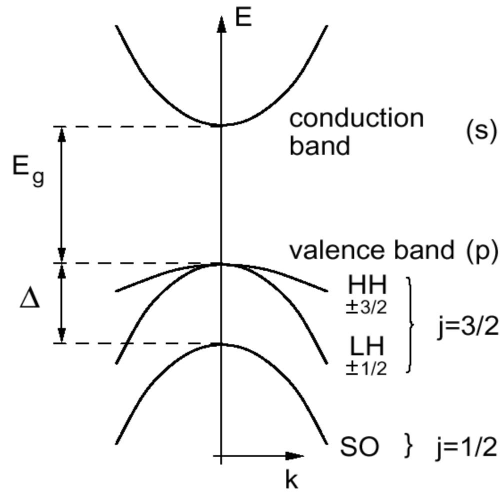


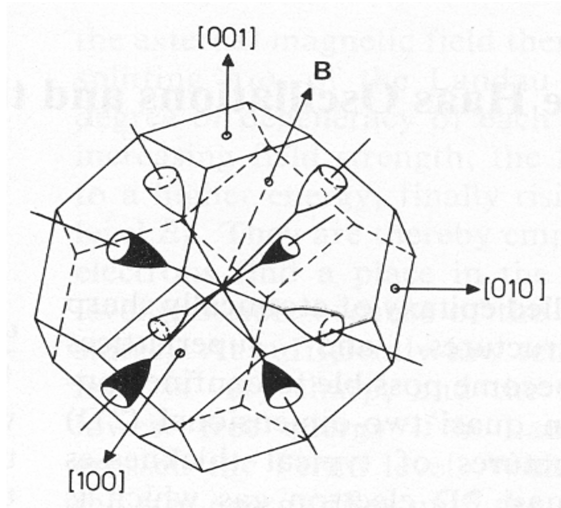




Ge (a) Si (b) GaAs (c)

Common features

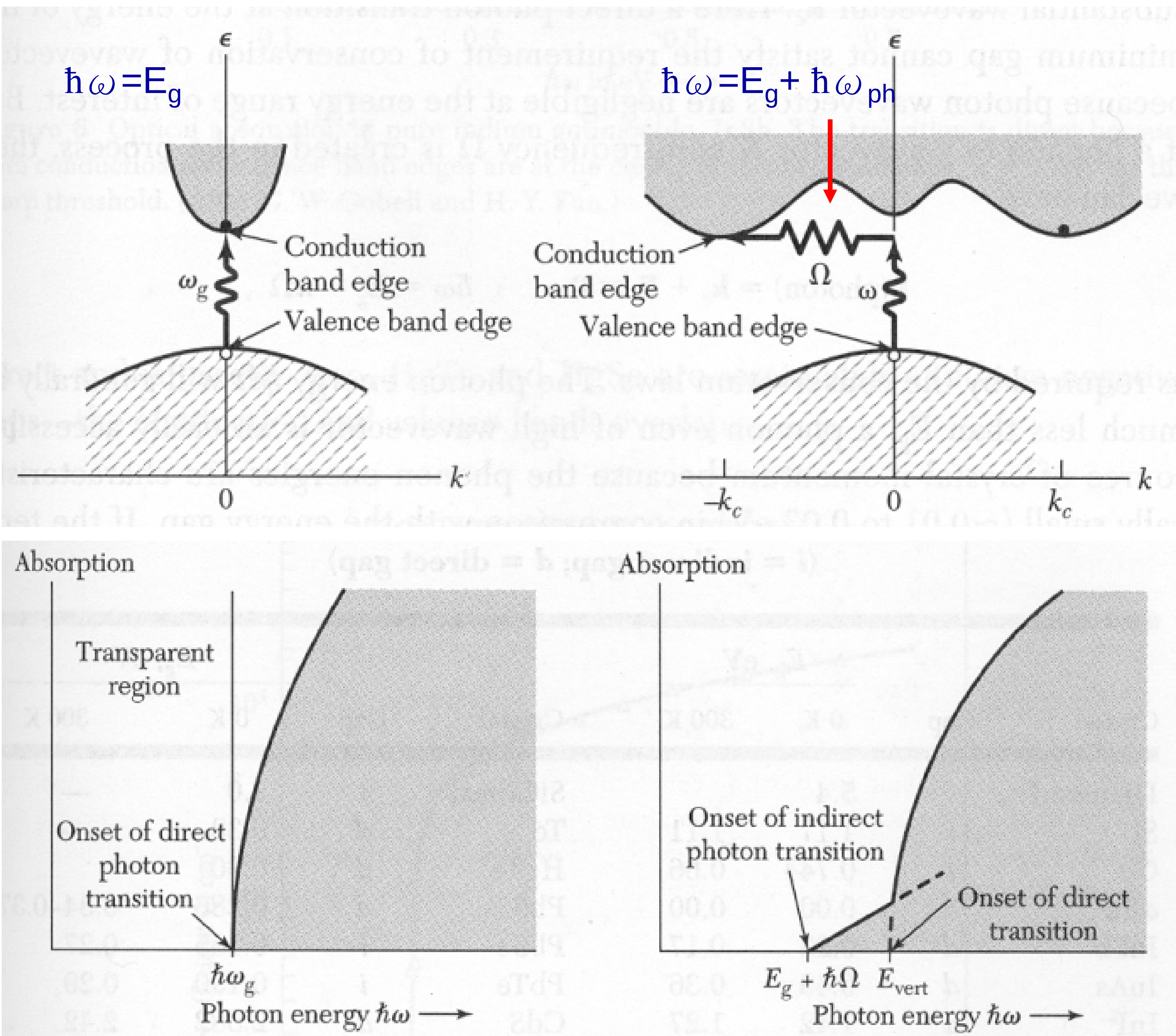




Useful parameters

	m_L/m_T	m_{HH}/m_{LH}	Δ
Si	0.91/0.19	0.46/0.16	0.044 eV
GaAs	0.063	0.5/0.076	0.3 eV

Direct band gap (GaAs, GaN…)   Indirect band gap (Si, Ge…)



Direct band gap semiconductor can emit light efficiently   1 μm=1.24 eV

Kubo-Greenwood formula

$$\sigma_{\alpha\beta}(\omega) = -\frac{e^2}{i\omega m_0}\left[n\delta_{\alpha\beta} + \frac{1}{m_0 V}\sum_{\ell m} \frac{f_\ell - f_m}{\hbar(\omega_{\ell m} + \omega + i\eta)} p^\alpha_{\ell m}\, p^\beta_{m\ell} \right]$$

$$\sigma'_{\alpha\beta} = \frac{\pi e^2}{\hbar\omega m_0^2}\frac{1}{V}\sum_{\ell m}\left(f_\ell - f_m \right) p^\alpha_{\ell m}\, p^\beta_{m\ell}\, \delta\left(\omega_{\ell m} + \omega\right)$$

$$\varepsilon_{\alpha\beta}(\omega) = 1 + \frac{4\pi i \sigma_{\alpha\beta}}{\omega}$$

$$\varepsilon''_{\alpha\beta} = \left(\frac{2\pi e}{m_0\omega}\right)^2 \frac{1}{V}\sum_{\ell m}\left(f_\ell - f_m \right) p^\alpha_{\ell m}\, p^\beta_{m\ell}\, \delta\left(\hbar\omega - \hbar\omega_{m\ell}\right)$$

- For Bloch states

$$\ell = (n, \vec{k}, s)$$

$$p^\alpha_{\ell m} = \left\langle n\vec{k}s \right| p_\alpha \left| m\vec{k}'s' \right\rangle \delta_{\vec{k},\vec{k}'}\delta_{s,s'}$$

$$\rightarrow \varepsilon''_{\alpha\beta} = \left(\frac{2\pi e}{m_0\omega}\right)^2 \left|P_{\alpha\beta}(\omega)\right|^2 D_j(\hbar\omega)$$

- Joint density of states

$$D_j(\hbar\omega) \equiv \frac{2}{V}\sum_{nm\vec{k}} \delta\left[\hbar\omega - \hbar\omega_{mn}(\vec{k})\right]$$

$$\left|P_{\alpha\beta}(\omega)\right|^2 D_j(\hbar\omega)$$

$$\equiv \frac{2}{V}\sum_{nm\vec{k}} (f_n - f_m)\, p^\alpha_{nm}(\vec{k})\, p^\beta_{mn}(\vec{k})\,\delta\left[\hbar\omega - \hbar\omega_{mn}(\vec{k})\right]$$

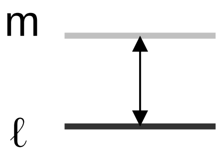
usually not sensitive to ω

Connection between absorption and interband transition

Transition rate per unit volume

- Fermi golden rule

$$R = \frac{2\pi}{\hbar}\frac{1}{V}\sum_{i,f}\left|\langle \psi_f | H' | \psi_i \rangle\right|^2 \delta\left(\varepsilon_{fi} - \hbar\omega\right)$$



$$\rightarrow R = \frac{2\pi}{\hbar}\frac{1}{V}\sum_{\ell m} f_\ell\left(1 - f_m\right)\left|\langle \psi_m | H' | \psi_\ell \rangle\right|^2 \delta\left(\varepsilon_{m\ell} - \hbar\omega\right) - \{\ell \leftrightarrow m\}\,\delta\left(\varepsilon_{\ell m} + \hbar\omega\right)$$

$$= \frac{2\pi}{\hbar}\frac{1}{V}\sum_{\ell m}\left(f_\ell - f_m\right)\left|\langle \psi_m | H' | \psi_\ell \rangle\right|^2 \delta\left(\varepsilon_{m\ell} - \hbar\omega\right)$$

$$H' = \frac{e}{mc}\vec{p}\cdot\vec{A}(\vec{x},t) \quad \text{(dipole approximation)}$$

$$\left|\langle \psi_{n\vec{k}} | H' | \psi_{m\vec{k}'} \rangle\right|^2 = \left(\frac{eA_0}{2mc}\right)^2 \left|\hat{e}\cdot\langle \psi_n | \vec{p} | \psi_m \rangle\right|^2 \delta_{\vec{k},\vec{k}'}\delta_{s,s'}$$

$$\rightarrow R(\omega) = \frac{2\pi}{\hbar}\left(\frac{eE_0}{2m\omega}\right)^2 \frac{2}{V}\sum_{nm\vec{k}}\left(f_n - f_m\right)\left|\hat{e}\cdot\langle \psi_n | \vec{p} | \psi_m \rangle\right|^2 \delta\left(\varepsilon_{mn} - \hbar\omega\right)$$

- Power loss/volume $= \hbar\omega R(\omega) = \dfrac{I_0}{n_R^2}\,\omega\,\varepsilon''_{\alpha\alpha}$

see ch 23

$\therefore$ energy loss is a result of optical transitions

Yu and Cardona, p.260

Direct interband transition

• Selection rule

$$\text{if } \Delta\ell \neq \pm 1$$

$$\text{then } p^{\alpha}_{nm}(\vec{k}) = \left\langle n\vec{k} \middle| p_\alpha \middle| m\vec{k} \right\rangle \sim 0$$

(ℓ is not exact for a Bloch electron)

• Joint density of states (2-band approximation)

$$D_j(\hbar\omega) = \frac{2}{V}\sum_{\vec{k}} \delta\left[\hbar\omega_{cv}(\vec{k}) - \hbar\omega\right]$$

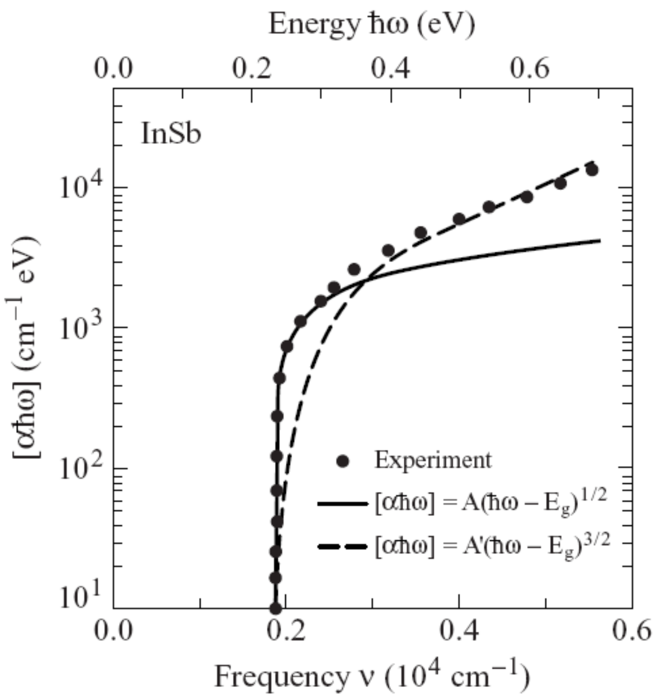
$$= \int [dk]\,\delta\left[\varepsilon_{cv}(\vec{k}) - \hbar\omega\right]$$

See ch 7 $$= \frac{1}{4\pi^3}\int \frac{dS_\varepsilon}{\left|\nabla_{\vec{k}}\varepsilon_{cv}\right|}$$

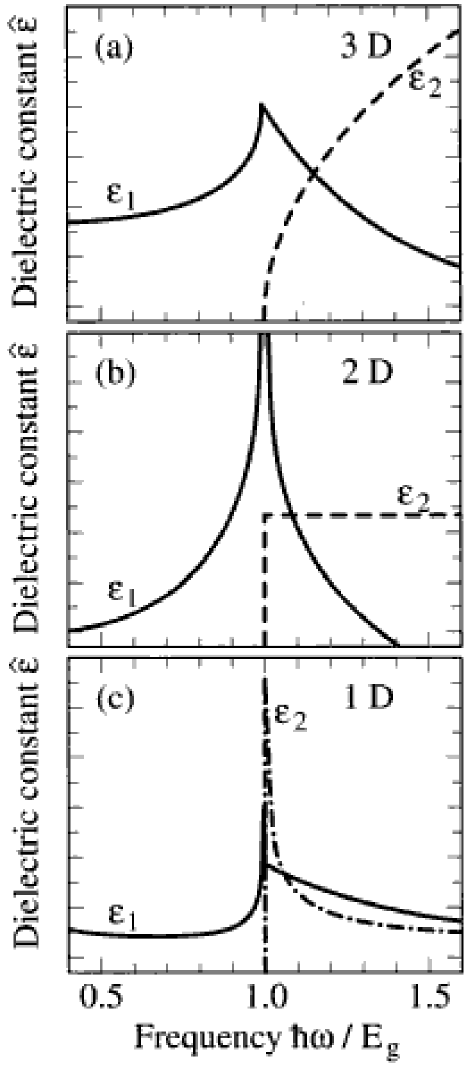
$$\varepsilon_{cv} = \varepsilon_g + \frac{\hbar^2 k^2}{2\mu}, \quad \frac{1}{\mu} = \frac{1}{m_v^*} + \frac{1}{m_c^*}$$

$$\to D_j(\hbar\omega) = \frac{(2\mu)^{3/2}}{2\pi^2\hbar^{5/2}}\sqrt{\omega - \omega_g}$$

$$\to \alpha(\omega) \propto \omega\varepsilon'' \propto \frac{\sqrt{\omega - \omega_g}}{\omega}$$



• Frequency-dependent dielectric constant



reflectivity $$r(\omega) \approx \frac{n_R - 1}{n_R + 1} \approx \frac{\varepsilon' - 1}{4}$$

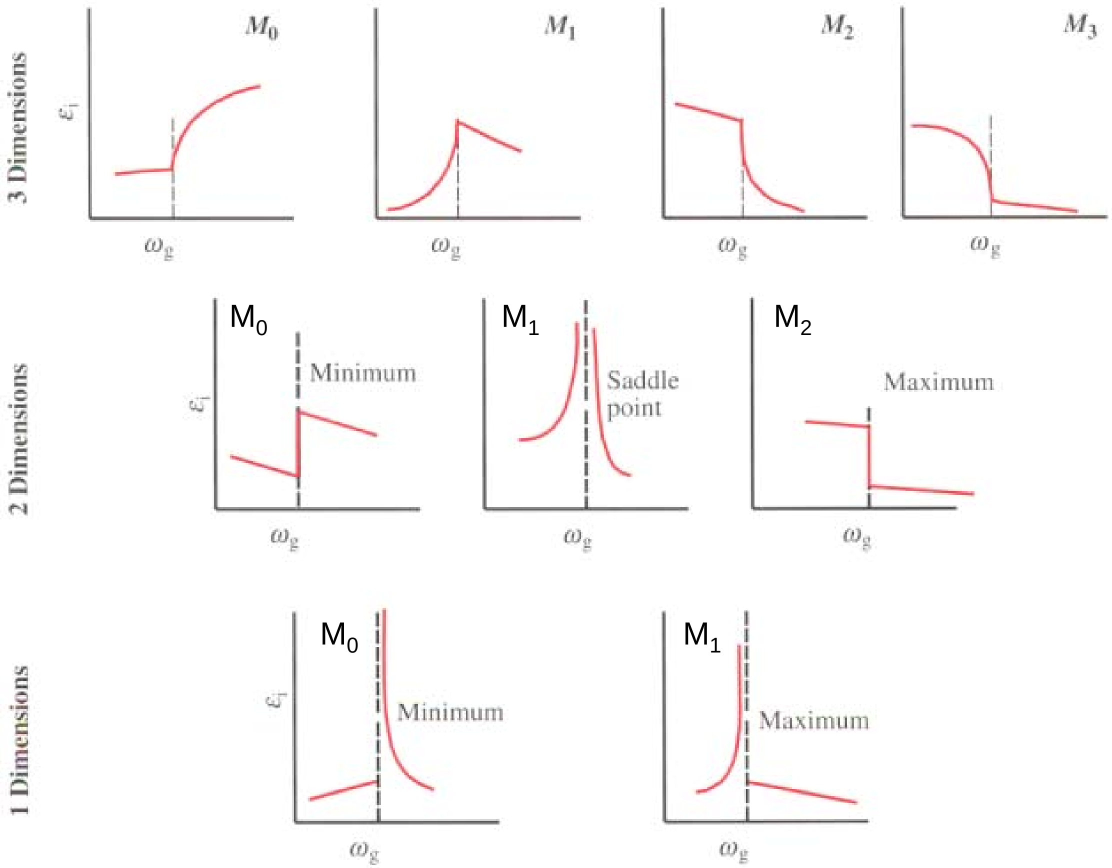
Dressel and Grüner, Electrodynamics of solids: optical properties of electrons in matter, p.157, 344 supplementary

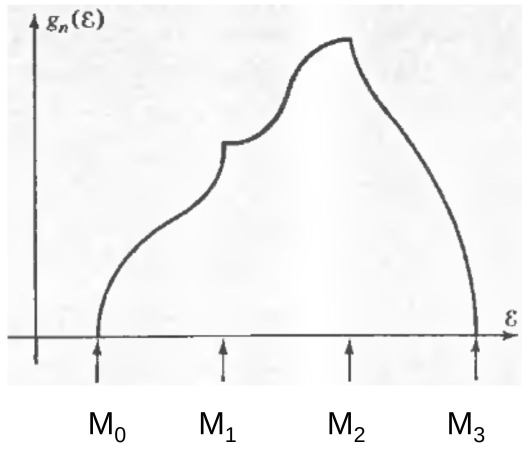
Yu and Cardona, p.263

Van Hove singularity

Type		D_j: $E < E_0$	D_j: $E > E_0$
Three dimensions	M_0	0	$(E - E_0)^{1/2}$
	M_1	$C - (E_0 - E)^{1/2}$	C
	M_2	C	$C - (E - E_0)^{1/2}$
	M_3	$(E_0 - E)^{1/2}$	0
Two dimensions	M_0	0	C
	M_1	$-\ln(E_0 - E)$	$-\ln(E - E_0)$
	M_2	C	0
One dimension	M_0	0	$(E - E_0)^{-1/2}$
	M_1	$(E_0 - E)^{-1/2}$	0

M_i, i: the number of negative coefficients in the quadratic expansion





Indirect interband transition (by emitting/absorbing phonons)

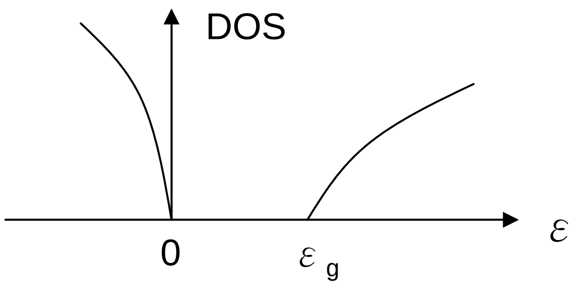
$$\alpha(\omega) \propto \frac{1}{V}\sum_{\vec{k},\vec{k}'} \delta\left[\hbar\omega_c(\vec{k}') - \hbar\omega_v(\vec{k}) - \hbar\omega \pm \hbar\omega_{ph}(\vec{q})\right], \quad \vec{q} = \vec{k}' - \vec{k}, \text{ neglect } \vec{q} - \text{dependence}$$

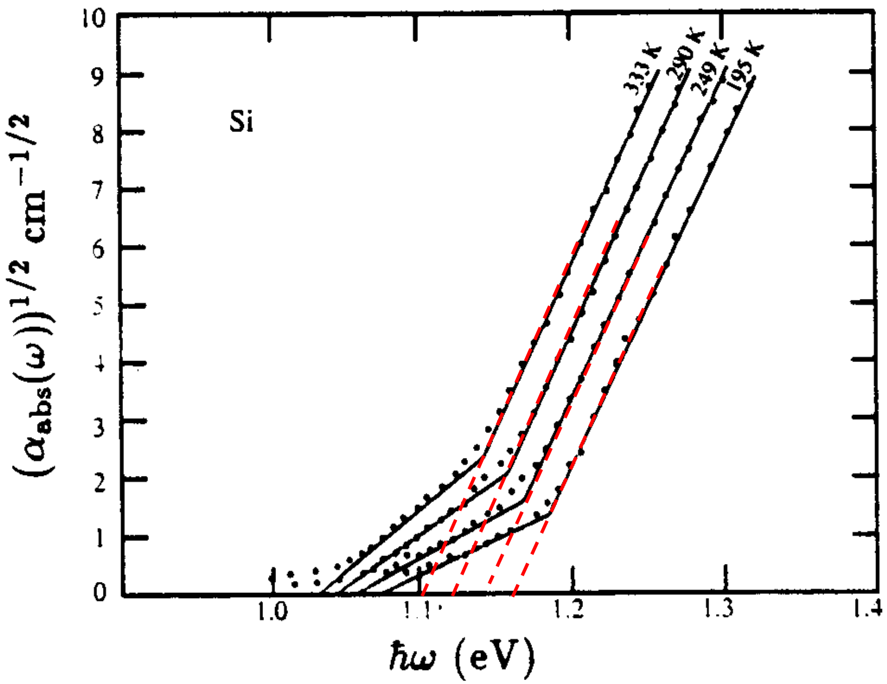
$$= \frac{1}{V}\int d\varepsilon \sum_{\vec{k}'} \delta\left[\hbar\omega_c(\vec{k}') - \varepsilon\right] \sum_{\vec{k}} \delta\left[\hbar\omega_v(\vec{k}) + \hbar\omega \mp \hbar\omega_{ph} - \varepsilon\right]$$

$$= V\int d\varepsilon D_c(\varepsilon) D_v(-\varepsilon + \hbar\omega \mp \hbar\omega_{ph})$$

$$\propto \int_{\varepsilon_g}^{\hbar\omega \mp \hbar\omega_{ph}} d\varepsilon \sqrt{\varepsilon - \varepsilon_g}\sqrt{-\varepsilon + \hbar\omega \mp \hbar\omega_{ph}}$$

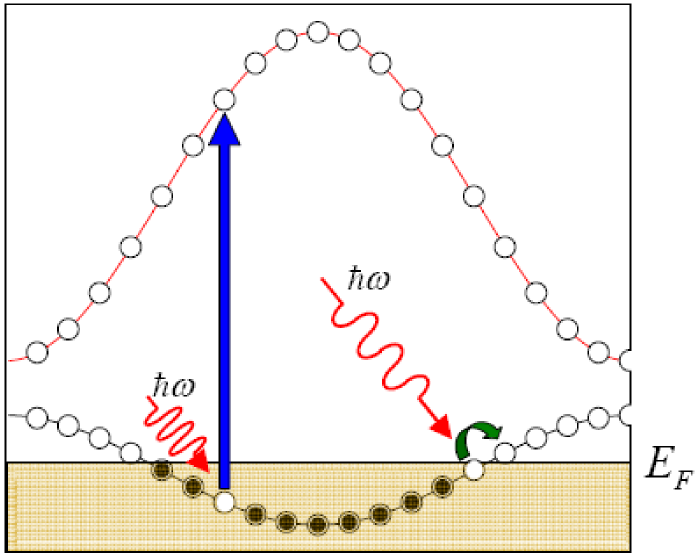
$$= \left(\hbar\omega \mp \hbar\omega_{ph} - \varepsilon_g\right)^2 \int_0^1 dy \sqrt{y}\sqrt{1-y}$$

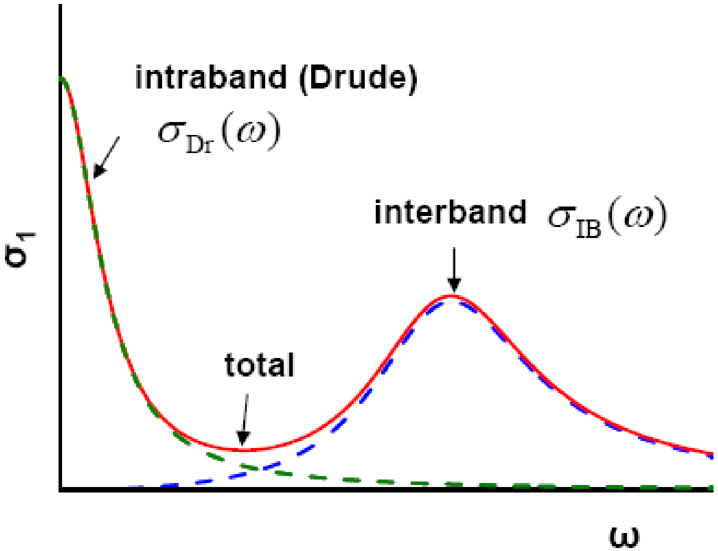




M. S. Dresselhaus, SOLID STATE PHYSICS, PART II, p.54

Summary: Intraband and interband transitions





$$\varepsilon(\omega) = 1 - \frac{4\pi}{\omega}\frac{\sigma_0}{\omega\tau + i}$$

For 3D

- Intraband absorption (semiconductor)

$$\alpha(\omega) \sim \omega^{-2} \quad (\omega\tau \gg 1)$$

- Direct interband transitions

$$\alpha(\omega) \sim \frac{\sqrt{\omega - \omega_g}}{\omega}$$

- Indirect interband transitions

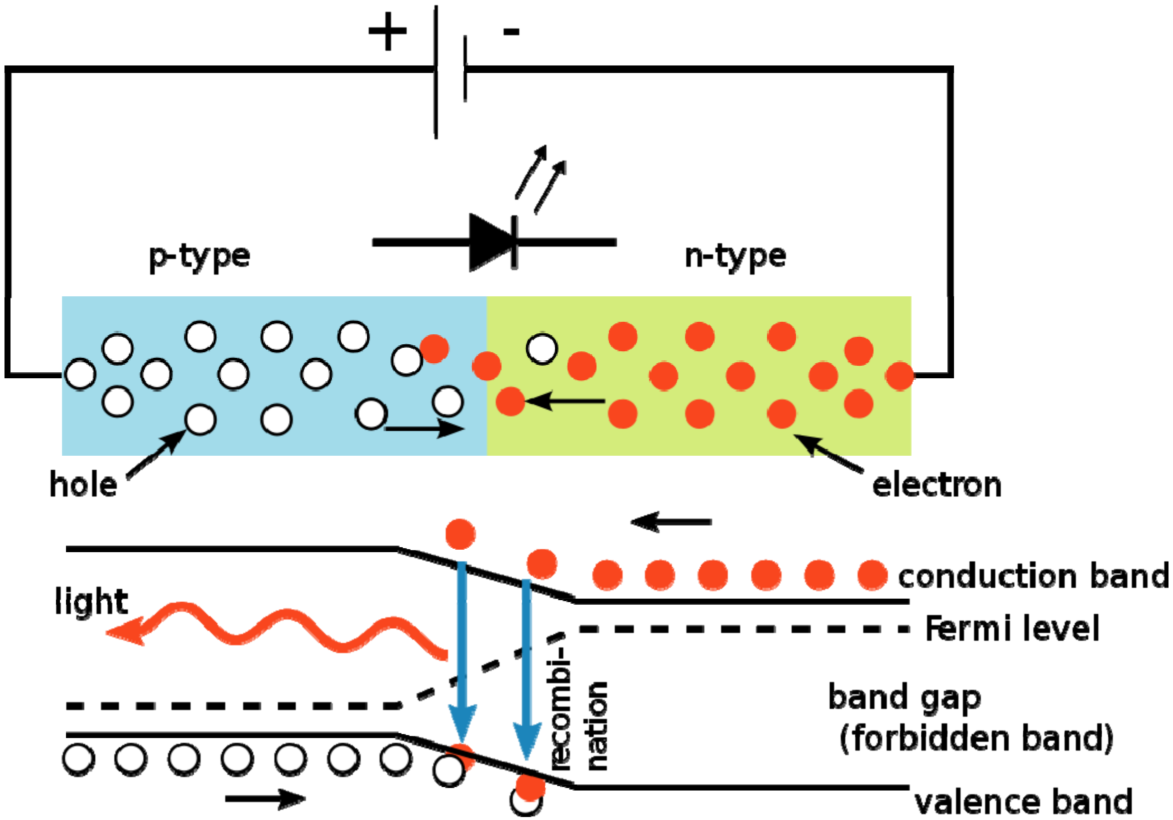
$$\alpha(\omega) \sim \left(\omega - \omega_g \pm \omega_{ph}\right)^2$$

$$\varepsilon = \varepsilon_{\mathrm{core}} + \frac{4\pi i}{\omega}\left(\sigma_{\mathrm{Drude}} + \sigma_{\mathrm{interband}}\right)$$

From Dr. A.B. Kuzmenko's slides

M. S. Dresselhaus, SOLID STATE PHYSICS, PART II, p.17、37

Light emitting diode



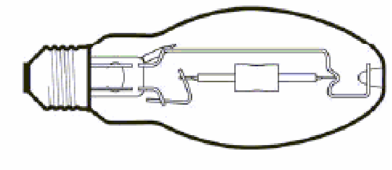
Conventional lighting

Incandescent

EU,Australia, CA…

Pros: Very cheap, great color
Cons: Very short lifetime, poor energy efficiency

High Intensity Discharge



Pros: Cheap, efficient
Cons: Poor color, long restart, short lifetime

Fluorescent

Pros: Cheap, energy efficient
Cons: Can not run in cold temp; difficult/costly to dim, control, Hg

Compact Fluorescent

Pros: Energy efficient
Cons: Poor color quality, Can not run in cold, High cost vs. Incand, Hg

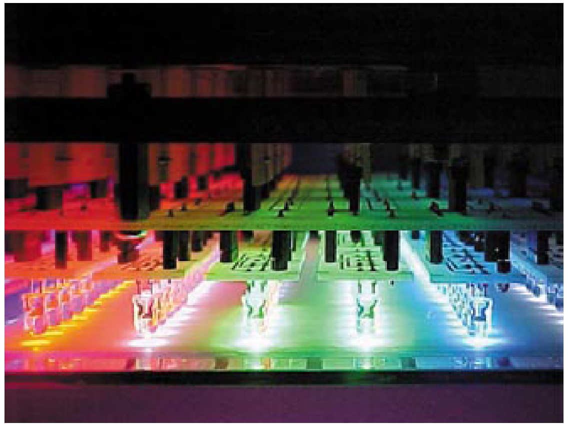
Halogen

Pros: Great color, focused light
Cons: Very short lifetime, poor energy efficiency

From S. Nakamura's slide

The Advantage of LED Lighting

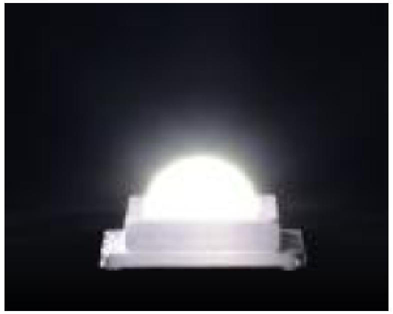
Long life – lifetimes can exceed 100,000 hours as compared to 1,000 hours for tungsten bulbs



Robustness – no moving parts, no glass, no filaments

Size – typical package is only 5 mm in diameter

Energy efficiency – up to 90% less energy used translates into smaller power supply

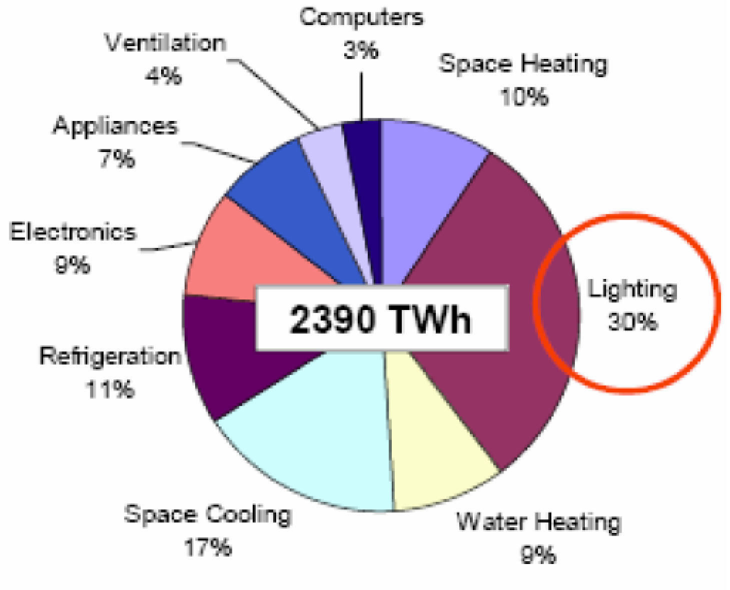


Non-toxicity – no mercury

Versatility – available in a variety of colors; can be pulsed

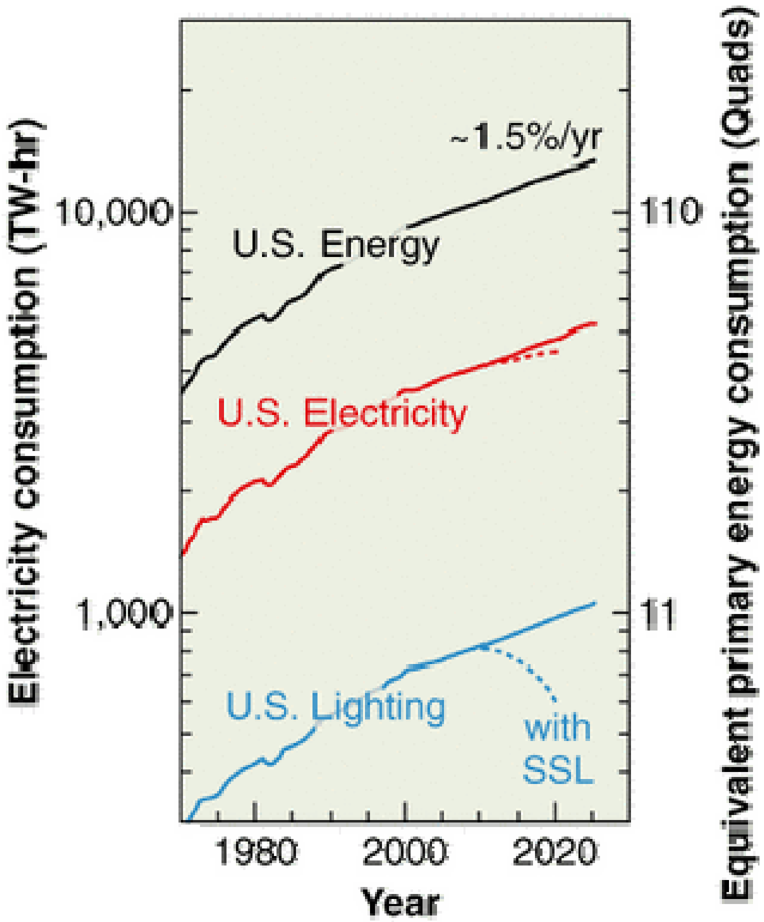
Cool – less heat radiation than HID or incandescent

From S. Nakamura's slide



Lighting is single biggest user of electricity

- Incandescent Light Bulb -1-4% efficient
- Fluorescent –15-25% efficient
- LED-25-52% efficient (90% theoretical)



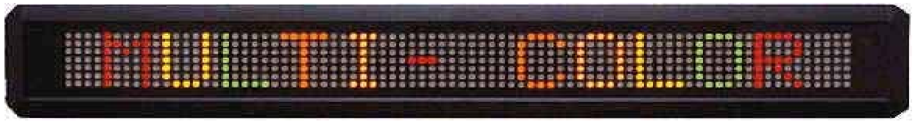
If a 150 lm/W Solid State White source were developed, then in the US alone:

- We would realize $115 Billion Savings in 2025
- Eliminate 258 million metric tons of Carbon
- …

From S. Nakamura's slide

The invention of blue-light LED

• Before blue LED



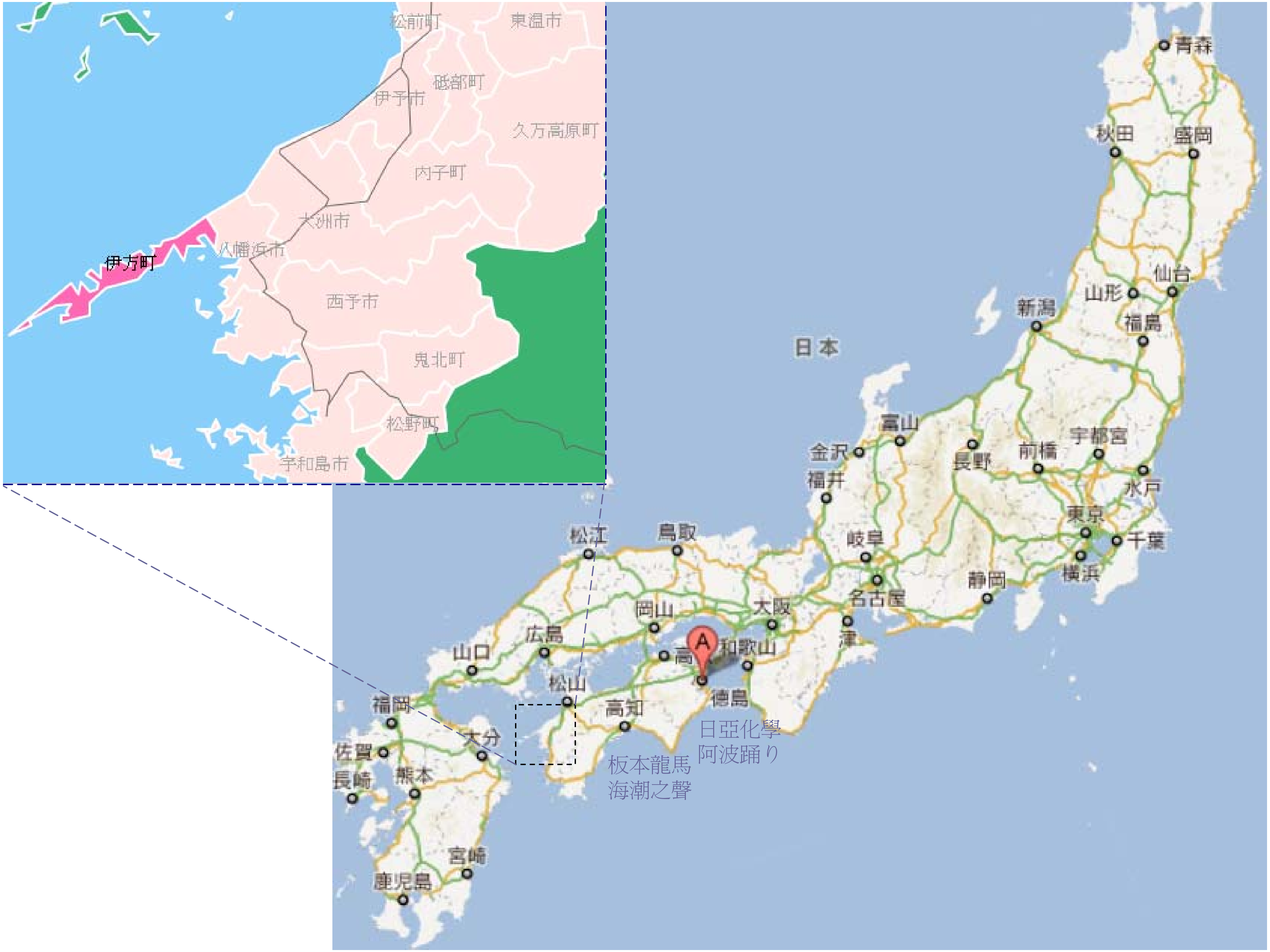
RCA, HP, Sony, Toshiba and more.

Analysts estimate that those companies, along with a couple dozen universities, spent roughly $1 billion in pursuit of blue-light devices since the 1960s.

• After blue LED

中村修二

THE MILLENNIUM TECHNOLOGY PRIZE 2006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東温市
砥部町
伊予市
久万高原町
内子町
大洲市
八幡浜市
伊方町
西予市
鬼北町
松野町
宇和島市
青森
秋田
盛岡
仙台
山形
新潟
福島
日本
富山
宇都宮
金沢
長野
前橋
水戸
福井
東京
千葉
松江
鳥取
岐阜
横浜
静岡
名古屋
大阪
岡山
広島
山口
和歌山
津
高
松山
徳島
高知
福岡
大分
佐賀
熊本
長崎
宮崎
鹿児島
日亞化學
阿波踊り
板本龍馬
海潮之聲

Shuji Nakamura and the blue laser diode

• 1977 BA, 1979 MA (EE), University of Tokushima

• 1979, joined Nichia, a company at Tokushima that was making a phosphor for CRT tubes and fluorescent lamps (R&D: 3 people) 日亞化學

Took him three years to grow commercial GaP crystals (red, yellow)

• 1982, switch to GaAs crystal growth. Took him 3 years to have a commercial product (infrared, red)

• 1985, switch to GaAlAs epitaxial wafer (infrared, red LEDs)

“For ten years I had worked very hard to make these products. I worked twelve hours a day, seven days a week, except holidays. I had a very, very small budget and had to make everything I needed myself. … My bosses always complained that my results were terrible, because I spent a lot of money, as far as they were concerned, and nothing sold.”

Nakamura and Ogawa at 1995

小川信雄

• 1988, boss (Ogawa) invested 3.3 million USDs on him to make blue LEDs.

• 1988~89, went to U. Florida for 1 year. Learned MOCVD.

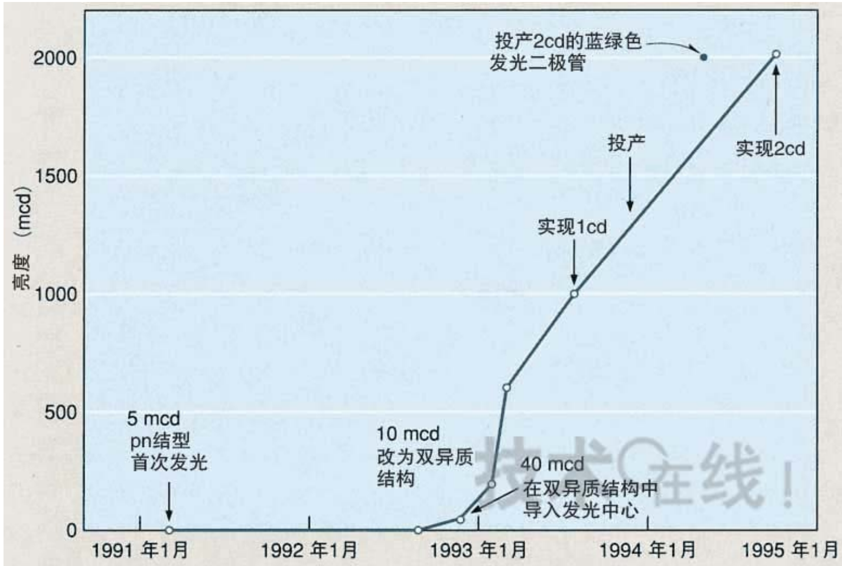
有機金屬化學氣相沉積法

http://archive.sciencewatch.com/jan-feb2000/sw_jan-feb2000_page3.htm

"I actually thought it looked very easy to make blue LEDs, I thought, blue means I just have to change the color—I just have to change the material."

"In 1989, there were two materials for making blue LEDs: ZnSe and GaN (3.4 eV)… The dislocation density for the former was less than 10^3 /cm^3. GaN was more than 10^{10} /cm^3. And when people wanted to make reliable LEDs and laser diodes, they knew that the dislocation density has to be lower than 10^3 or even 10^2. This is just physics."

- 1989, switch to GaN. Spent two years modifying his reactor and succeeded in making the two-flow MOCVD reactor at 1990.
- 1991~2, made *n*-type, then *p*-type GaN
- 1993, the first commercial blue LEDs
- 1995, switch to laser diode.
- 1997, the first commercial blue laser diode.



公司專利獎金: 兩萬日圓

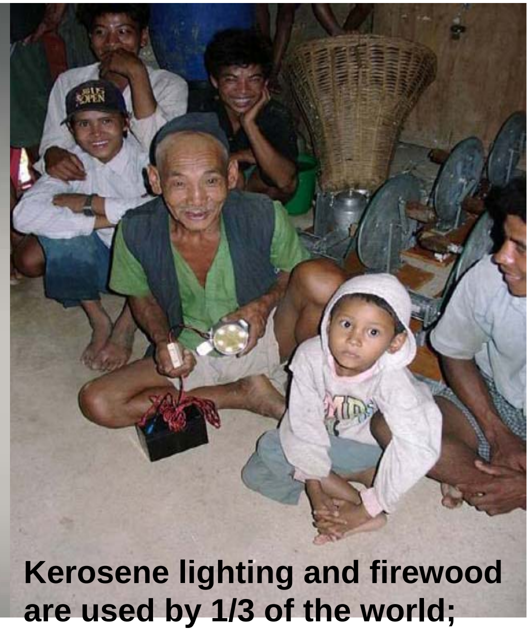
- 2004, 一審200億円勝訴
- 2005, 二審8億4000万円和解

- 1999~2000, quit Nichia, move to UCSB

"*Within a month, as word got out of his decision to leave Nichia, Nakamura was offered professorships at 10 U.S. universities and two European ones, and at five U.S. companies*."

See a nice "Interview with Nakamura": Scientific American, July, 2000

UV Water Purifier



Kerosene lighting and firewood are used by 1/3 of the world; they cause countless fires and are very inefficient (0.03 lm/w).

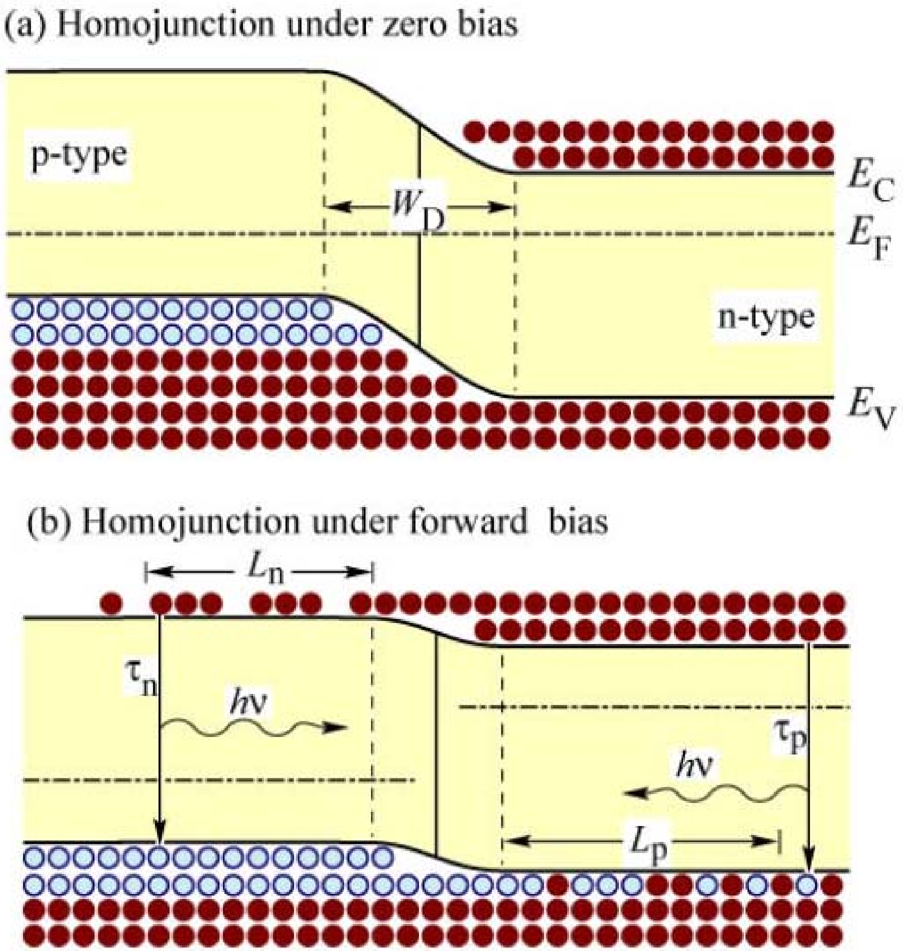
LED-backlit LCD TV

The future is now

VOLUME 9, NUMBER 9 PHYSICAL REVIEW LETTERS NOVEMBER 1, 1962

COHERENT LIGHT EMISSION FROM GaAs JUNCTIONS

R. N. Hall, G. E. Fenner, J. D. Kingsley, T. J. Soltys, and R. O. Carlson
General Electric Research Laboratory, Schenectady, New York
(Received September 24, 1962)



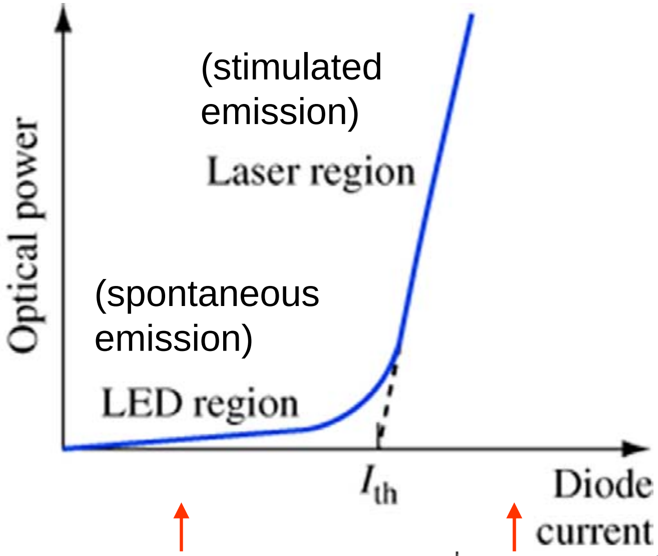
- Population Inversion:

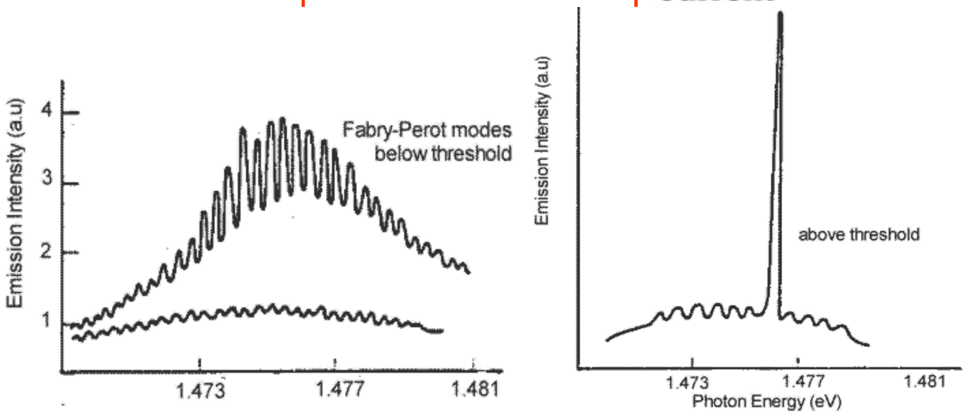
More electrons in the CB at energies near Ec than electrons in VB near Ev

- The region where the population inversion occurs develops a layer along the junction called an active layer

From Khanh Kieu's slide

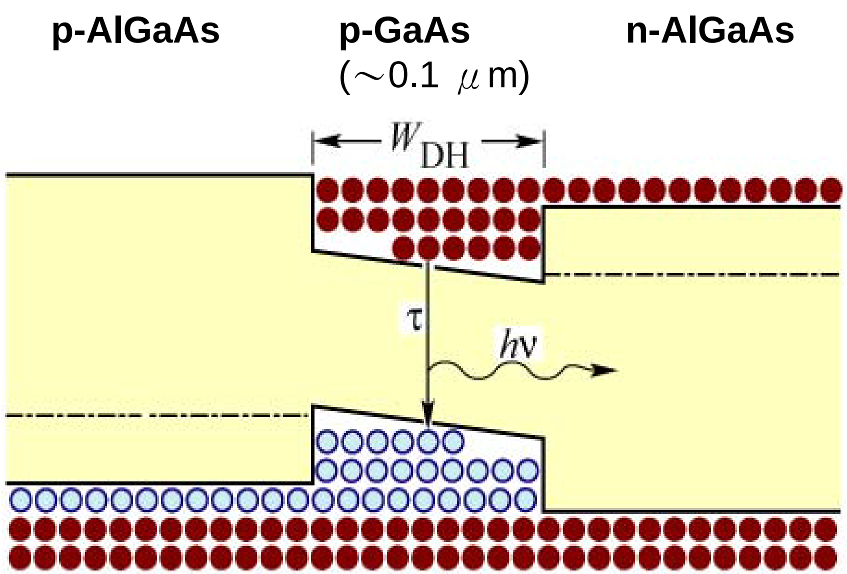
Homojunction diode laser





- Threshold current density is high, 1000 A/cm^2 at 77 K, 10^5 at RT)
- Solution → Double heterostructure laser

Double heterostructure diode laser



active layer

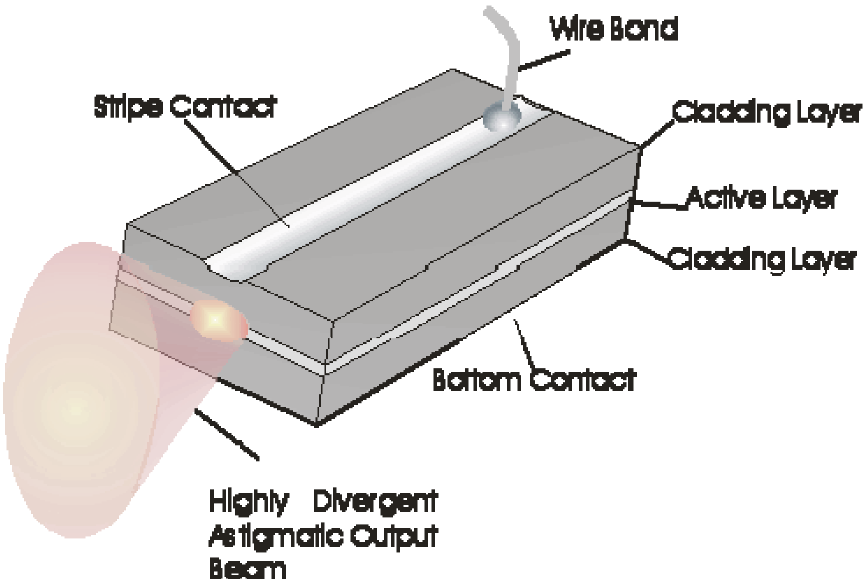
- Higher band gap materials have a lower refractive index
- AlGaAs layers provide lateral optical confinement

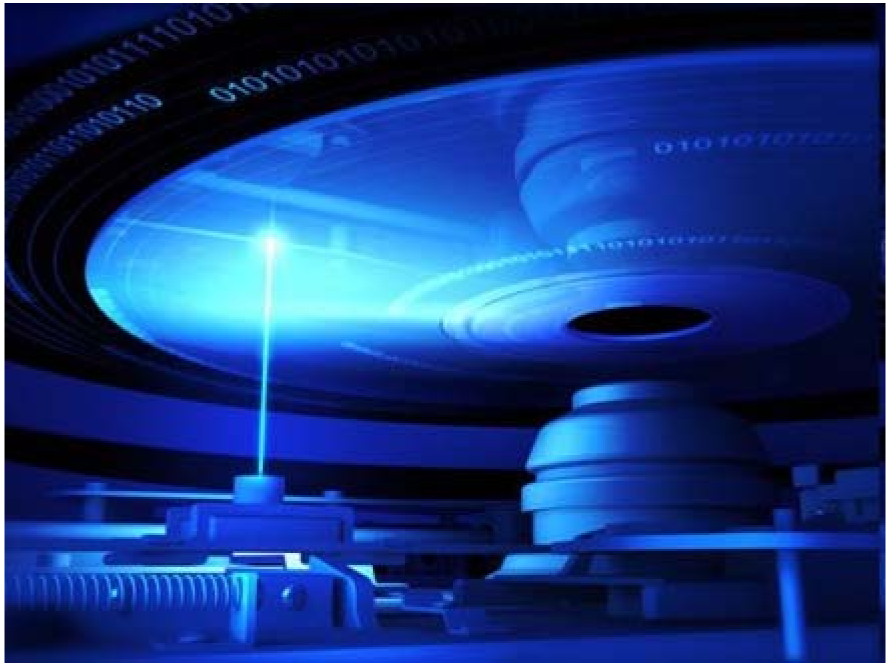
From Khanh Kieu's slide

From Khanh Kieu's slide

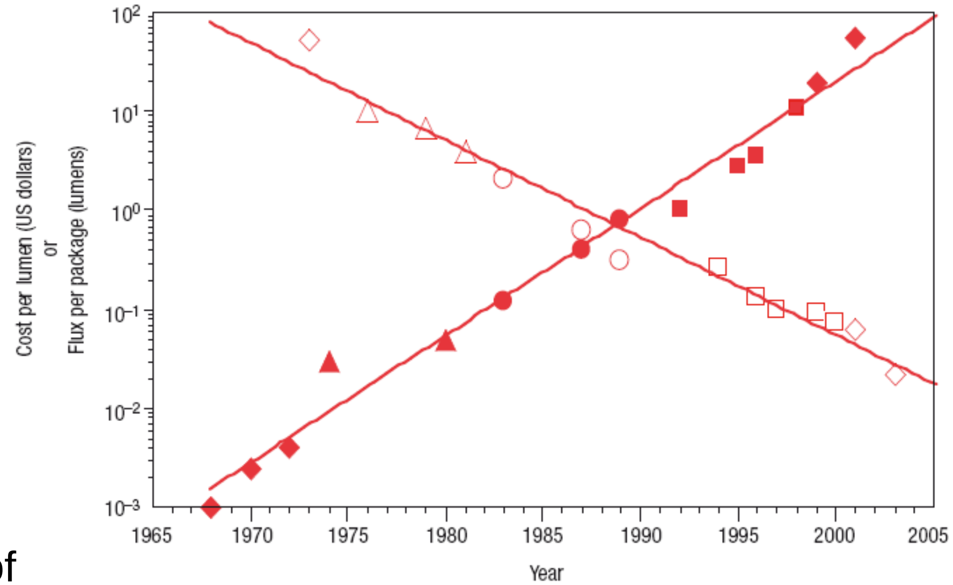
Diode laser: Applications

- Telecommunication (Optical fiber…)
- Data storage (DVD player…)
- Material processing (welding, heat treating…)
- Laser pumping
- Medicine (diagnostics, LASIK, cosmetic…)
- Laser printers, bar-code readers



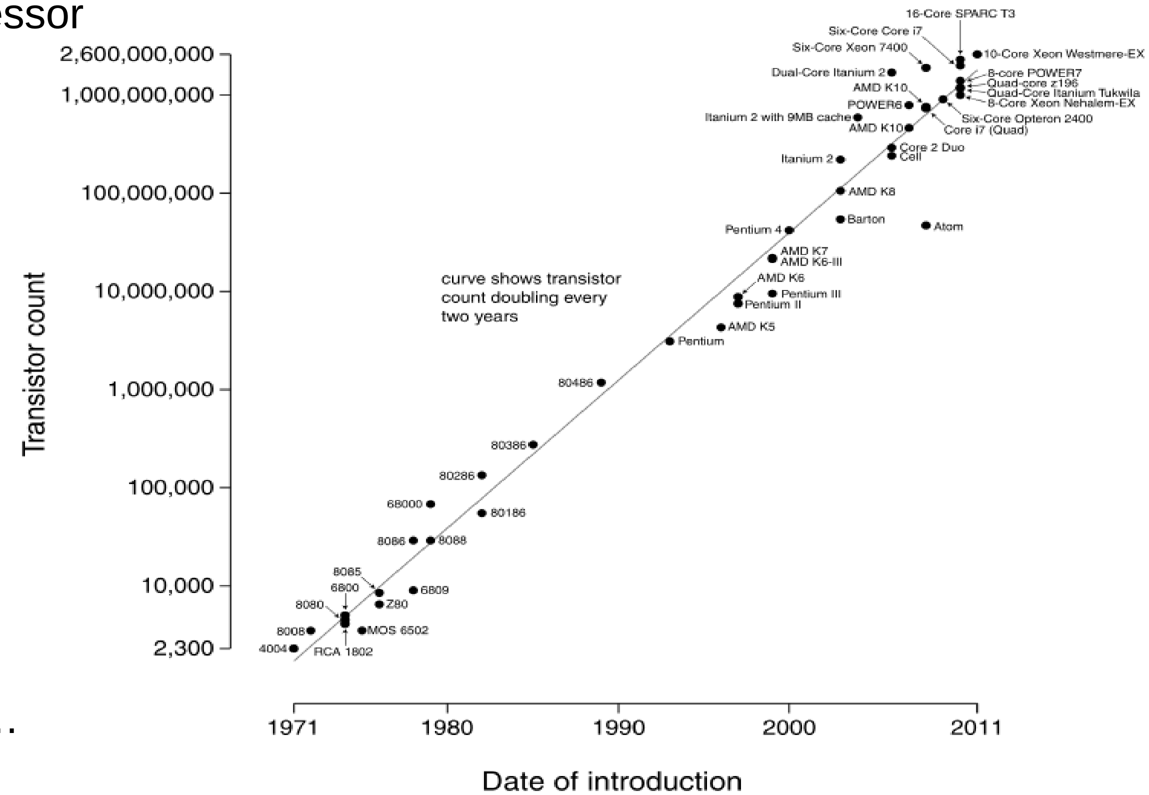


• Haitz's law of LED



Cree breaks 200 Lu/W barrier, Feb 2010.

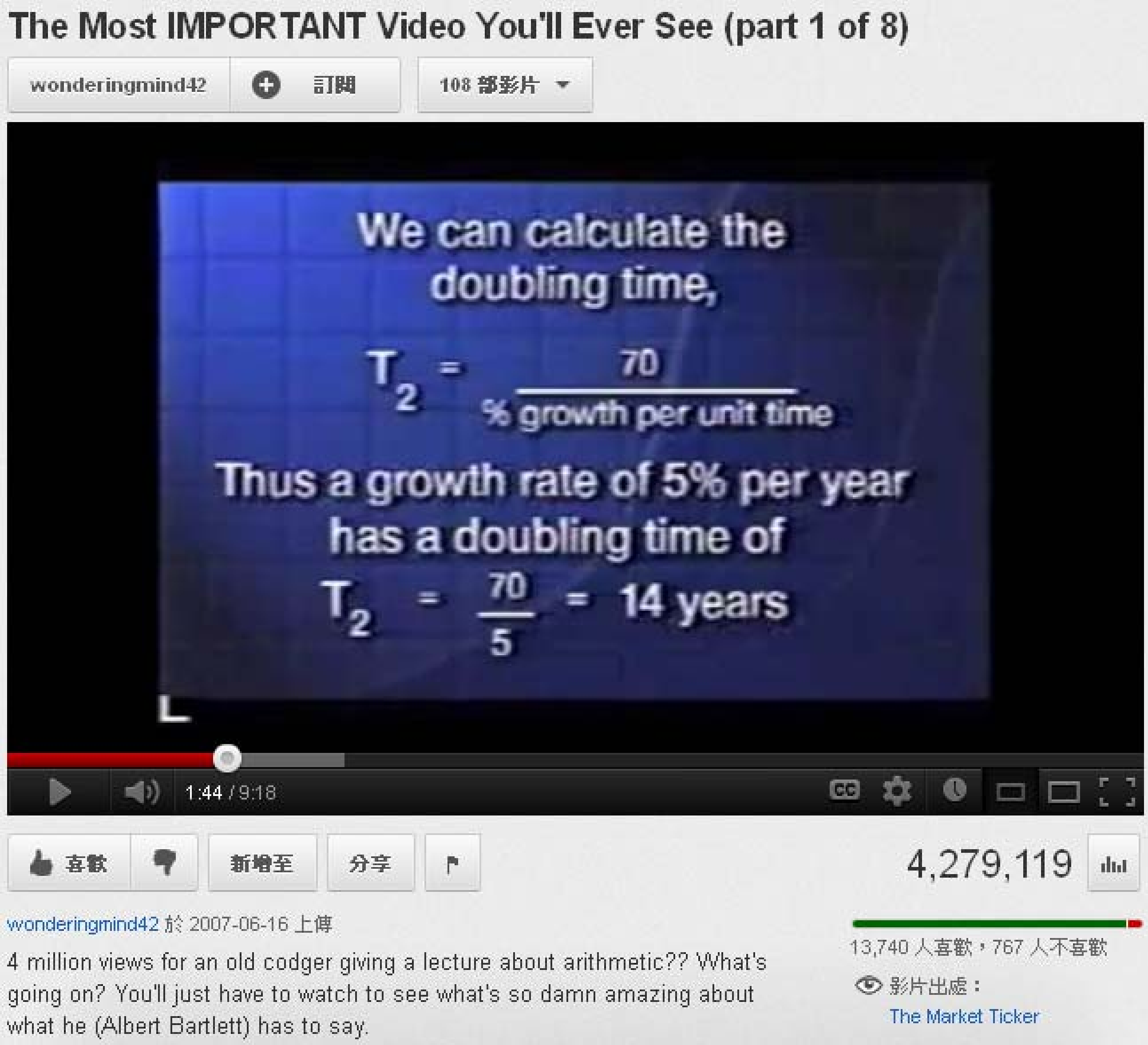
• Moore's law of microprocessor transistors



And more…

Time (11/19/07)

Finally, I'd like to talk some more about exponential growth



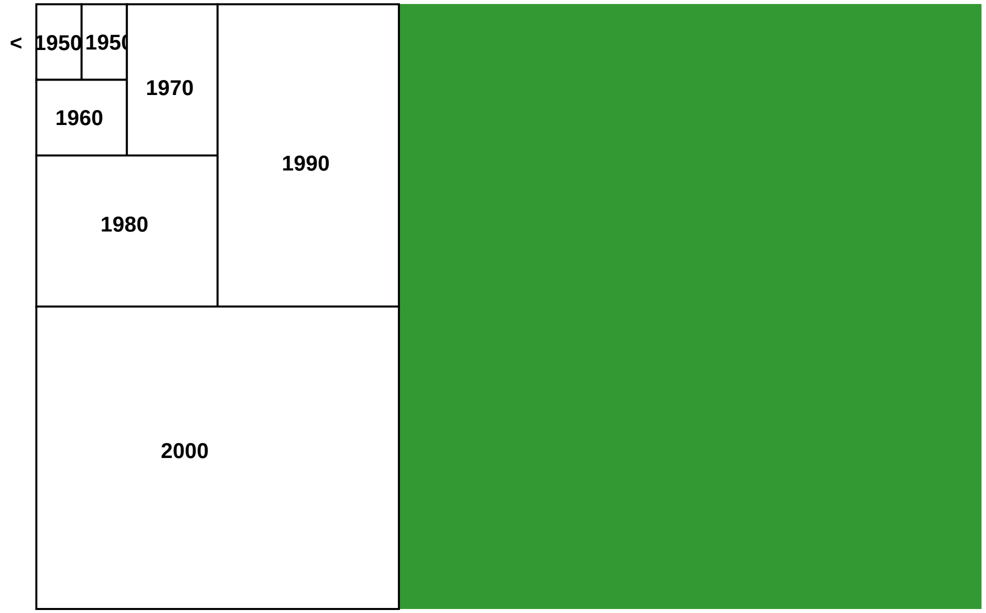
http://www.youtube.com/watch?v=F-QA2rkpBSY&feature=related

"The growth in any doubling time is greater than
the total of all the preceding growth !"

- Grains of wheat on a chessboard

Square number	Grains on square	Total grains
1	1	1
2	2	3
3	4	7
4	8	15
5	16	31
6	32	63
7	64	127
64	2^{63}	2^{64}-1

- Oil consumption, 7% per year

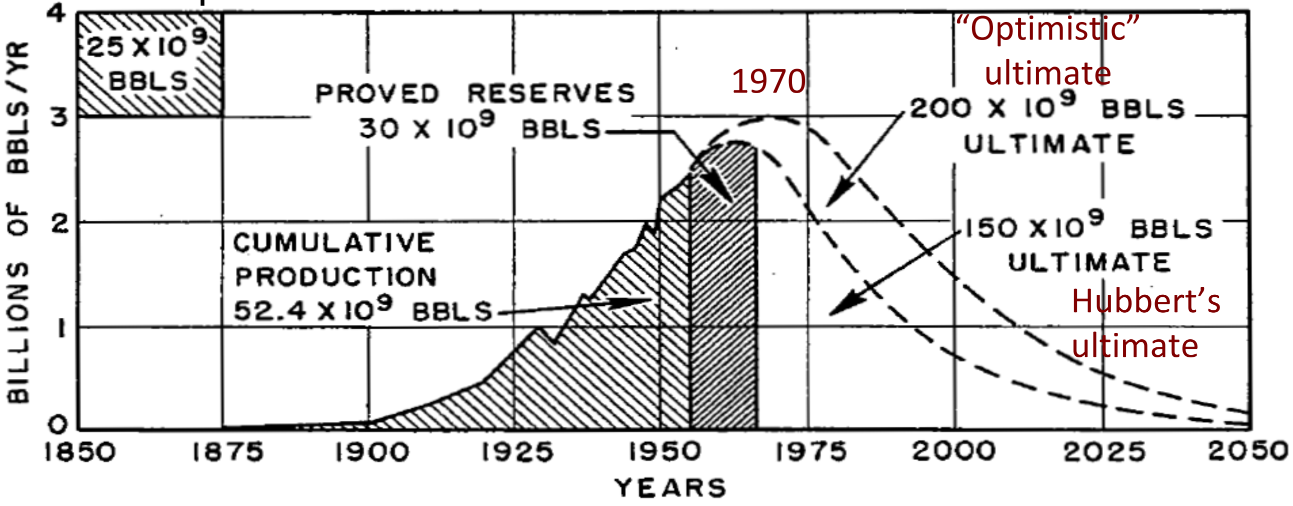


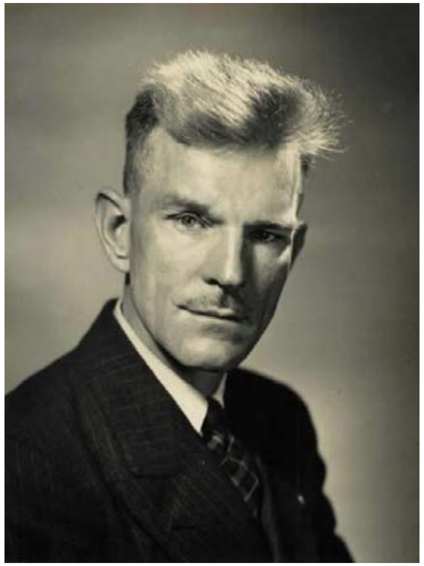
Carter on energy (1977)

"… and in each of those decades (the 1950's and 1960's)
more oil was consumed than in all of mankind's previous history."

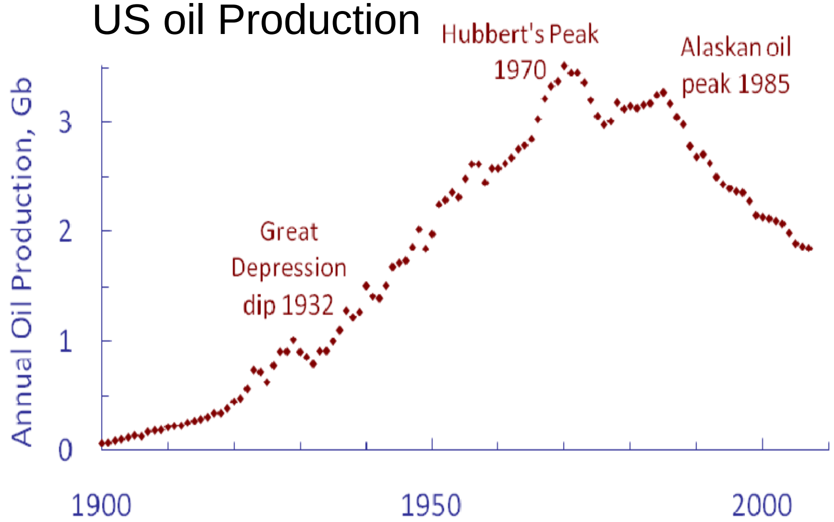
Hubbert peak (predicted by M.K. Hubbert in 1956)

US oil production

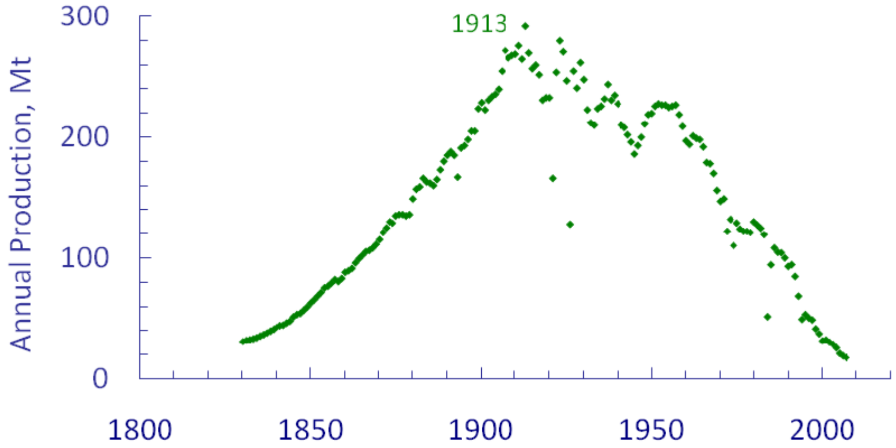




US oil Production

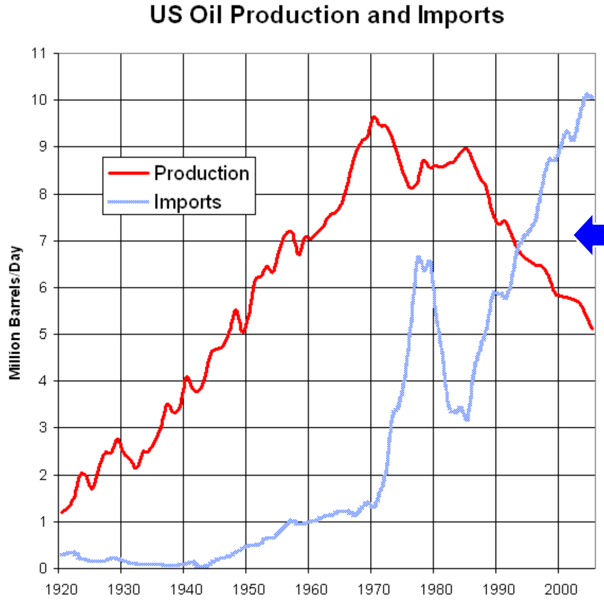


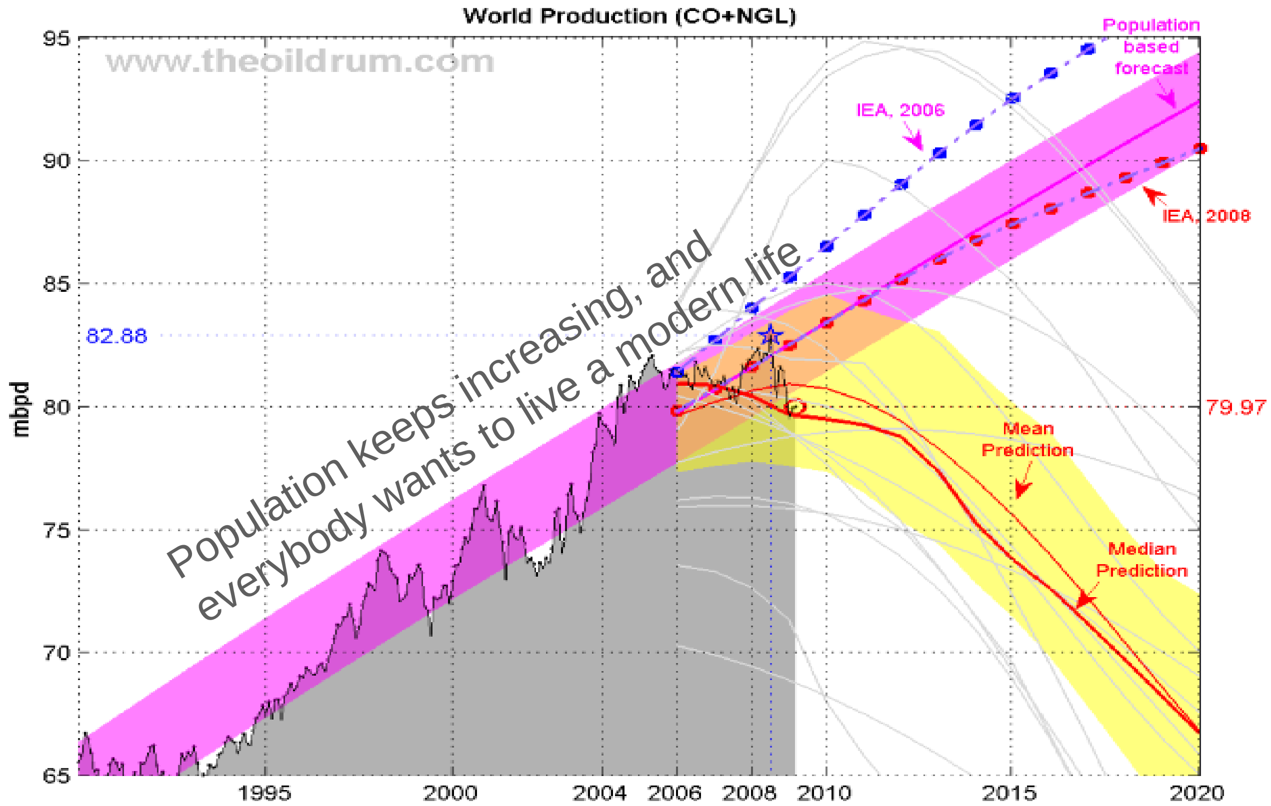
UK Coal Production



From D. Rutledge's slides

What does this really mean?

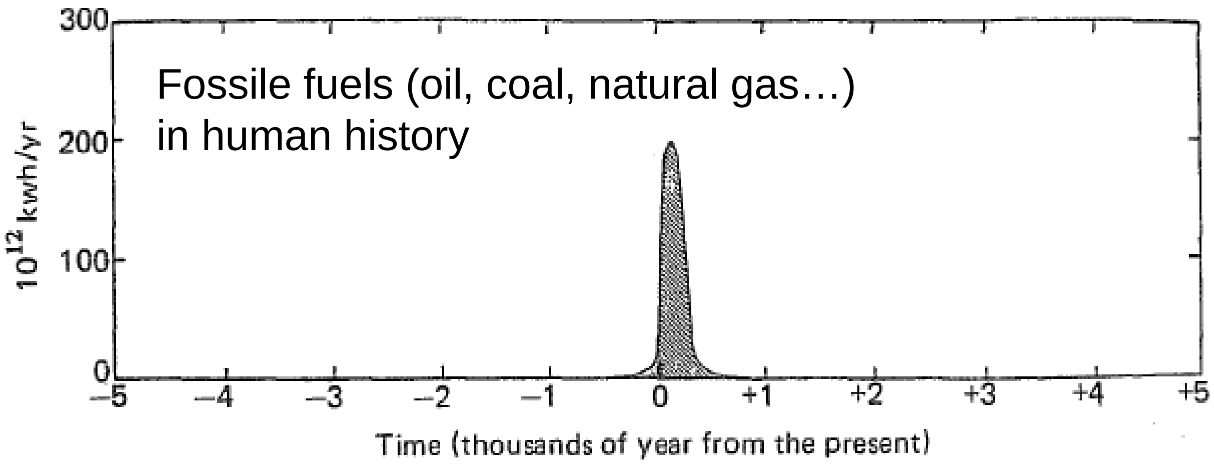




The median forecast is calculated from 15 models that are predicting a peak before 2020. 95% of the predictions sees a production peak between 2008 and 2010. The magenta area is the 95% confidence interval for the population-based model.

http://www.theoildrum.com/node/5521#more

What does this really mean?



Historians will look back at our generation as the generation of "oil peak".

UN Bruntland Commission:

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."