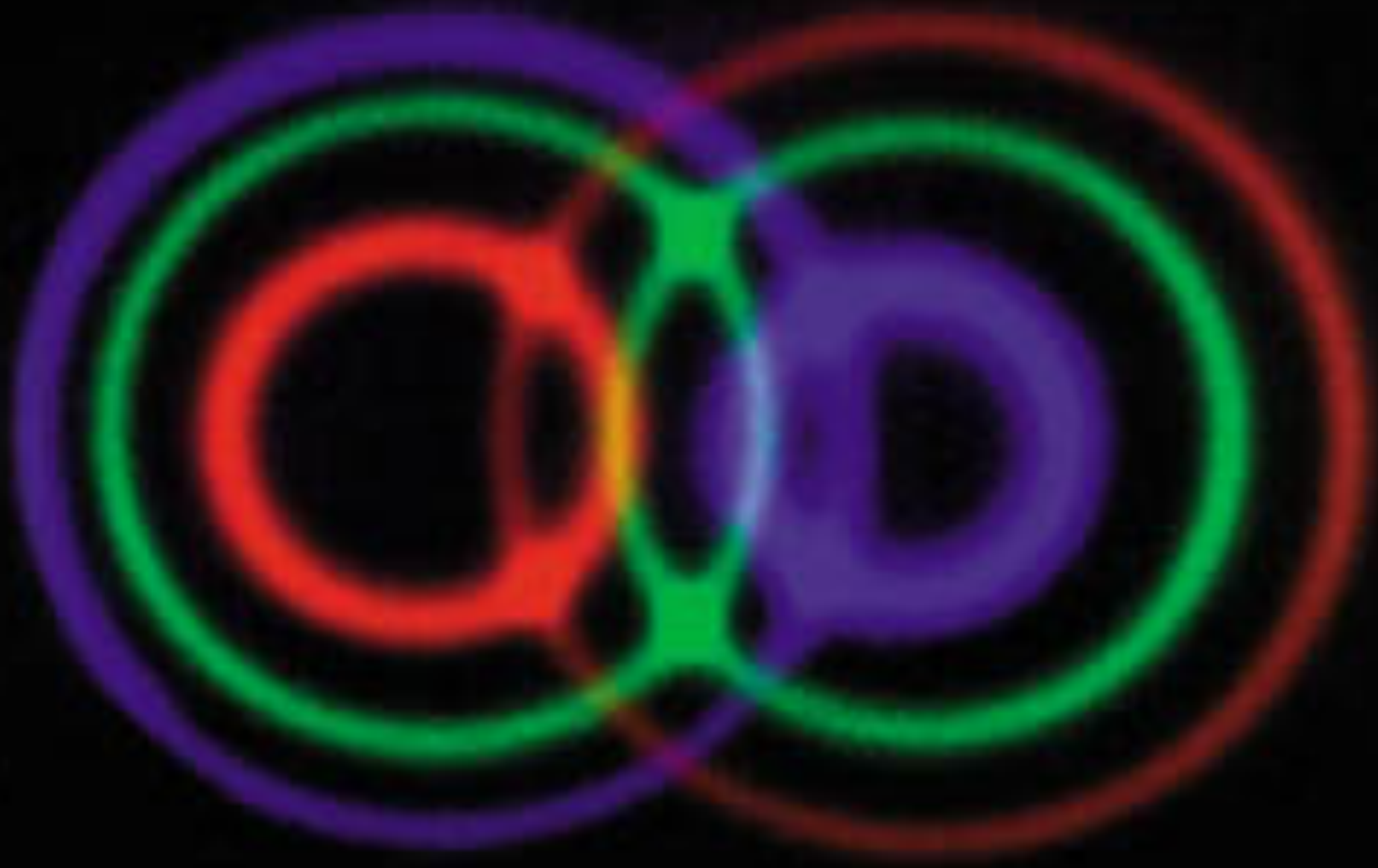
Fotonica ed elettronica quantistica



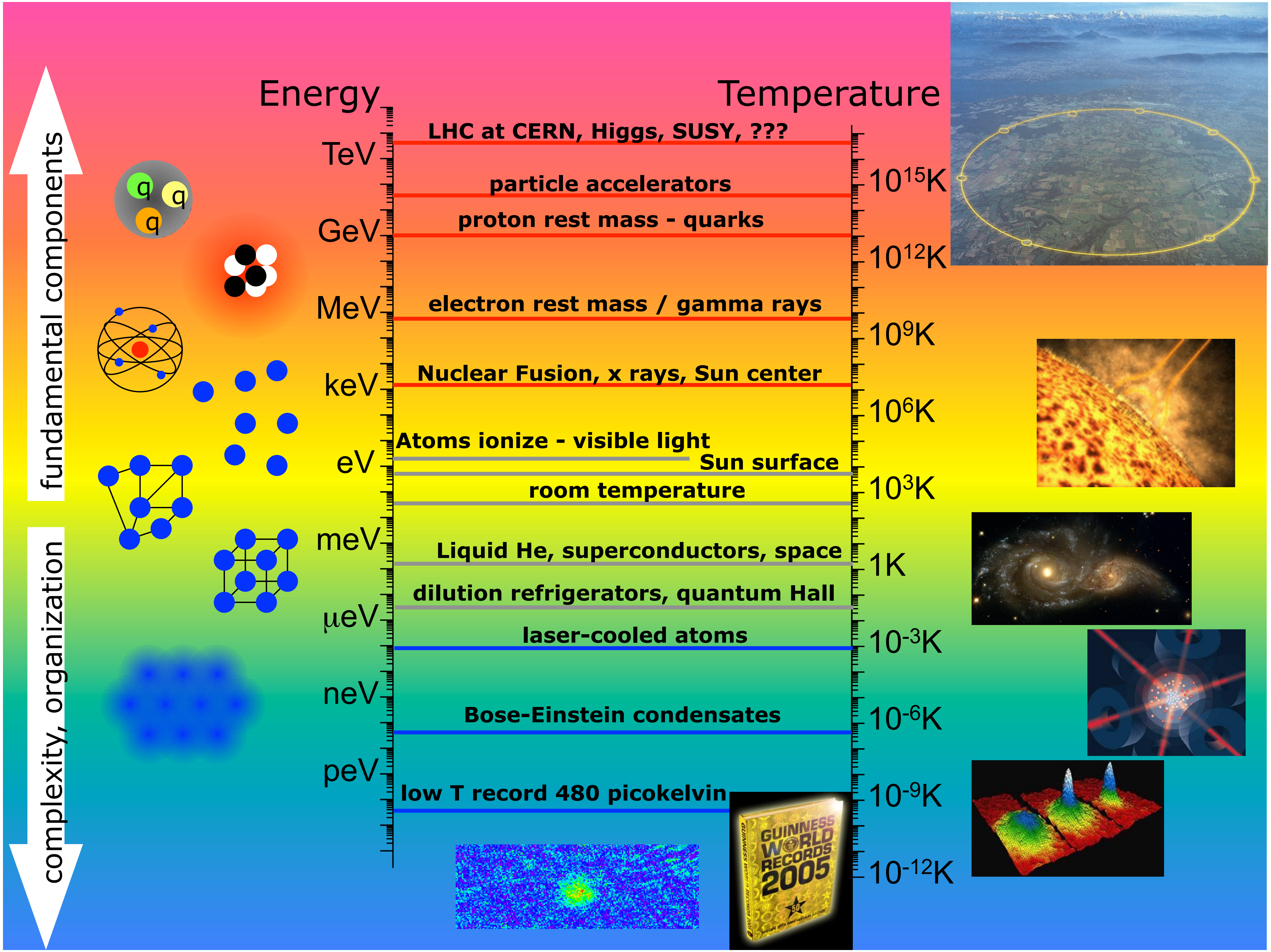
http://www.dsf.unica.it/~fotonica/teaching/fotonica.html

Fotonica ed elettronica quantistica

Quantum optics
- Quantization of electromagnetic field
- Statistics of light, photon counting and noise;
- HBT and correlation; g1 e g2 coherence; antibunching; single photons
- Squeezing
- Quantum cryptography
- Quantum computer, entanglement and teleportation

Light-matter Interaction
- Two-level atom
- Laser physics
- Spectroscopy
- Electronics and photonics at the nanometer scale
- Cold atoms
- Photodetectors
- Solar cells

http://www.dsf.unica.it/~fotonica/teaching/fotonica.html



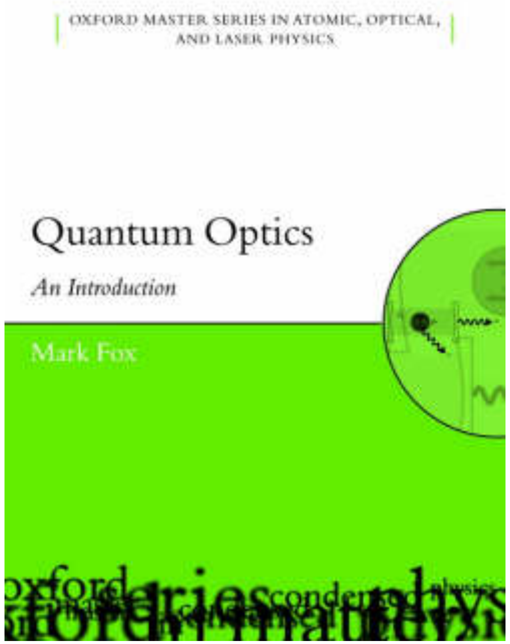
fundamental components
complexity, organization
q
q
q
Energy
Temperature
TeV
GeV
MeV
keV
eV
meV
µeV
neV
peV
LHC at CERN, Higgs, SUSY, ???
particle accelerators
proton rest mass - quarks
electron rest mass / gamma rays
Nuclear Fusion, x rays, Sun center
Atoms ionize - visible light
Sun surface
room temperature
Liquid He, superconductors, space
dilution refrigerators, quantum Hall
laser-cooled atoms
Bose-Einstein condensates
low T record 480 picokelvin
10^{15}K
10^{12}K
10^{9}K
10^{6}K
10^{3}K
1K
10^{-3}K
10^{-6}K
10^{-9}K
10^{-12}K
GUINNESS WORLD RECORDS 2005

Nobel Prizes in Physics

2010 - Andre Geims, Konstantin Novoselov
2009 - Charles K. Kao, Willard S. Boyle, George E. Smith
2007 - Albert Fert, Peter Gruenberg
2005 - Roy J. Glauber, John L. Hall, Theodor W. Hänsch
2001 - Eric A. Cornell, Wolfgang Ketterle, Carl E. Wieman
1997 - Steven Chu, Claude Cohen-Tannoudji, William D. Phillips
1989 - Norman F. Ramsey, Hans G. Dehmelt, Wolfgang Paul
1981 - Nicolaas Bloembergen, Arthur L. Schawlow, Kai M. Siegbahn
1966 - Alfred Kastler
1964 - Charles H. Townes, Nicolay G. Basov, Aleksandr M. Prokhorov
1944 - Isidor Isaac Rabi
1930 - Venkata Raman
1921 - Albert Einstein
1907 - Albert A. Michelson

Textbook

Quantum Optics An Introduction
(Oxford Master Series in Physics No. 15)
di: Mark Fox
Editore: Oxford University Press



Other books:
B.A. Saleh, M.C. Teich - *Fundamentals of Photonics* - 1991, John Wiley & Sons, Inc
Scully, Zubairy – *Quantum Optics* - Cambridge University Press
Meystre, Sargent – *Elements of Quantum Optics* – Springer Verlag
Walls, Milburn – *Quantum Optics* - Springer Verlag
Gerry, Knight – *Introductory Quantum Optics* – Cambrdidge University Press
Yamamoto, Imamoglu – *Mesoscopic quantum optics* - Wiley

Come passare l’esame

3 CFU = 24 ore di lezione

Esercizi a casa

Seminario finale (o interrogazione)

Quantization
of the e.m. field

Classical harmonic oscillators

Mass attached to spring

$$F = m\ddot{x} = -kx \quad \Rightarrow \quad \ddot{x} = -\omega^2 x, \quad \omega = \sqrt{\frac{k}{m}}$$

$$x(t) = x_0 \sin\omega t; \quad p_x(t) = m\omega x_0 \cos\omega t$$

$$E_{HO} = \frac{p_x^2}{2m} + \frac{1}{2} m\omega^2 x^2 = \frac{m\omega^2 x_0^2}{2}\left(\cos^2 \omega t + \sin^2 \omega t\right)$$

Light waves as classical harmonic oscillators I

Maxwell, mon amour

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

$$\nabla \cdot B = 0$$

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

$$\nabla \times B = \mu_0 \left(j + \varepsilon_0 \frac{\partial \mathcal{E}}{\partial t} \right)$$

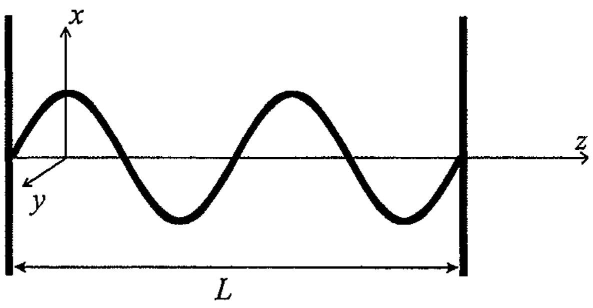


Fig. 2.1. Cavity with perfectly conducting walls located at $z = 0$ and $z = L$. The electric field is polarized along the x-direction.

EM standing wave in cavity

$$\mathcal{E}_x(z,t) = \mathcal{E}_0 \sin kz \sin \omega t$$

$$-\frac{\partial B_y}{\partial z} = \varepsilon_0 \mu_0 \frac{\partial \mathcal{E}_x}{\partial t} = \varepsilon_0 \mu_0 \mathcal{E}_0 \omega \sin kz \cos \omega t \qquad \left[c = \frac{\omega}{k} = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} \right]$$

$$B_y(z,t) = \frac{\varepsilon_0 \mu_0 \mathcal{E}_0 \omega}{k} \cos kz \cos \omega t = \frac{\mathcal{E}_0}{c} \cos kz \cos \omega t = B_0 \cos kz \cos \omega t$$

Light waves as classical harmonic oscillators II

Energy of EM standing wave in cavity

$$U = \frac{1}{2}\left(\varepsilon_0 \mathcal{E}^2 + \frac{B^2}{\mu_0}\right)$$

Local energy density
– to be integrated in space across cavity volume

$$E_{el} = \frac{1}{2}\varepsilon_0 A \int_0^L \mathcal{E}_0^2 \sin^2 kz \sin^2 \omega t dz = \frac{1}{4}\varepsilon_0 V \mathcal{E}_0^2 \sin^2 \omega t$$

$$E_{mag} = \frac{1}{4\mu_0} V B_0^2 \cos^2 \omega t$$

$$E_{em} = \frac{V}{4}\left(\varepsilon_0 \mathcal{E}_0^2 \sin^2 \omega t + \frac{B_0^2}{\mu_0}\cos^2 \omega t\right) = \frac{V}{4}\varepsilon_0 \mathcal{E}_0^2 \left(\sin^2 \omega t + \cos^2 \omega t\right)$$

Light waves as classical harmonic oscillators III

New coordinates

$$q(t) = \sqrt{\frac{\varepsilon_0 V}{2\omega^2}}\mathcal{E}_0 \sin \omega t$$

$$p(t) = \sqrt{\frac{V}{2\mu_0}} B_0 \cos \omega t = \sqrt{\frac{V}{2\mu_0}} \frac{\mathcal{E}_0}{c} \cos \omega t = \sqrt{\frac{\varepsilon_0 V}{2}}\mathcal{E}_0 \cos \omega t$$

$$p = \dot{q}$$

$$\ddot{q} = \dot{p} = -\omega^2 q$$

$$E_{em} = \frac{1}{2}\left(p^2 + \omega^2 q\right)$$

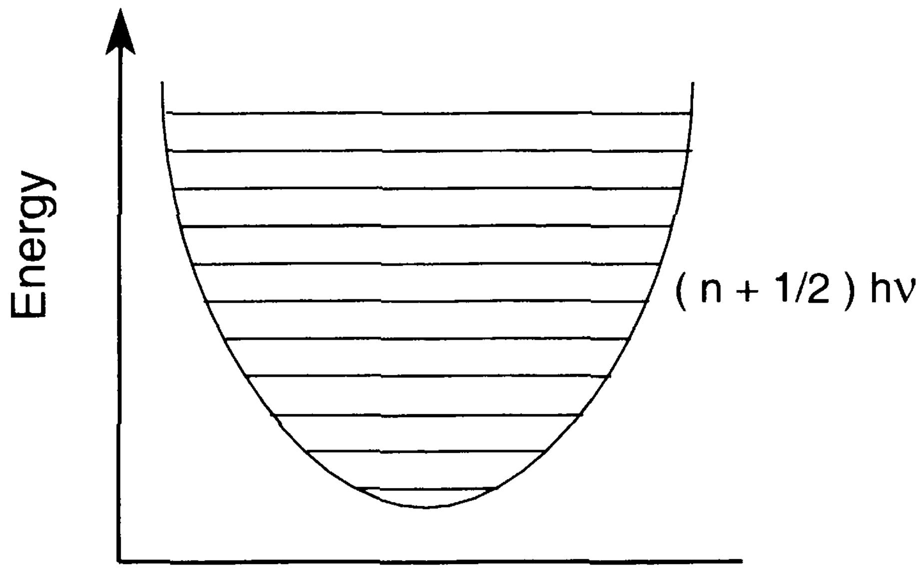
$$q(t) = \sqrt{m}\, x(t)$$

$$p(t) = \frac{1}{\sqrt{m}} p_x(t)$$

Light as a quantum harmonic oscillator

$$E_n = \left(n + \frac{1}{2}\right)\hbar\omega$$

$$\Delta x \Delta p_x \geq \frac{\hbar}{2} \qquad \Rightarrow \qquad \Delta q \Delta p \geq \frac{\hbar}{2}$$



$$q(t) = \sqrt{m}\,x(t)$$

$$p(t) = \frac{1}{\sqrt{m}}\,p_x(t)$$

Vacuum field

$$U = \frac{1}{2}\left(\varepsilon_0 \mathcal{E}^2 + \frac{B^2}{\mu_0}\right)$$

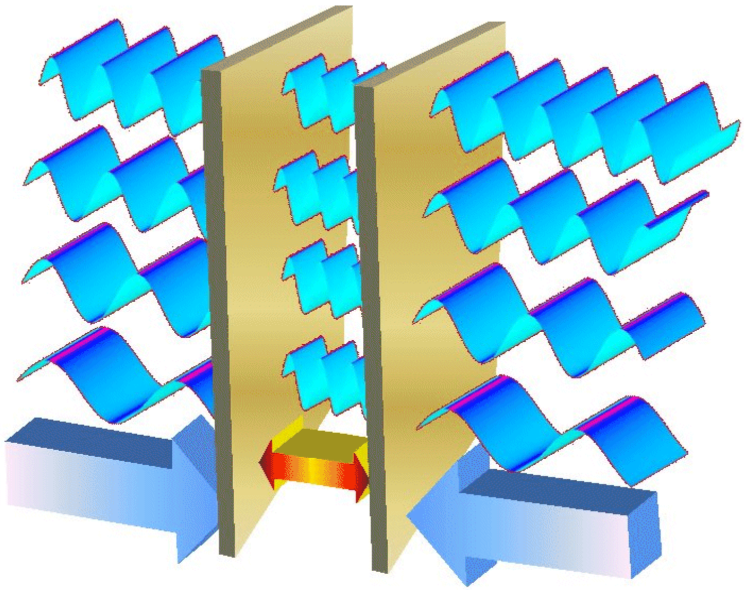
$$E_0 = \frac{1}{2}\hbar\omega = 2 \times \int \frac{1}{2}\varepsilon_0 \mathcal{E}_{vac}^2 dV$$

$$\mathcal{E}_{vac} = \sqrt{\frac{\hbar\omega}{2\varepsilon_0 V}}$$

Casimir force

$$F_{Casimir} = \frac{\pi^2 \hbar c}{240 L^4} A$$

Between parallel perfect mirrors



Numerical examples:

For A = 1 m^2 and L = 10^{-3} m, F = 1.3 10^{-15} N.
For A = 10^{-4} m^2 and L = 10^{-6} m, F = 1.3 10^{-7} N.

Quantum Mechanical Actuation of Microelectromechanical Systems by the Casimir Force

H. B. Chan, V. A. Aksyuk, R. N. Kleiman, D. J. Bishop, Federico Capasso*

www.sciencemag.org SCIENCE VOL 291 9 MARCH 2001

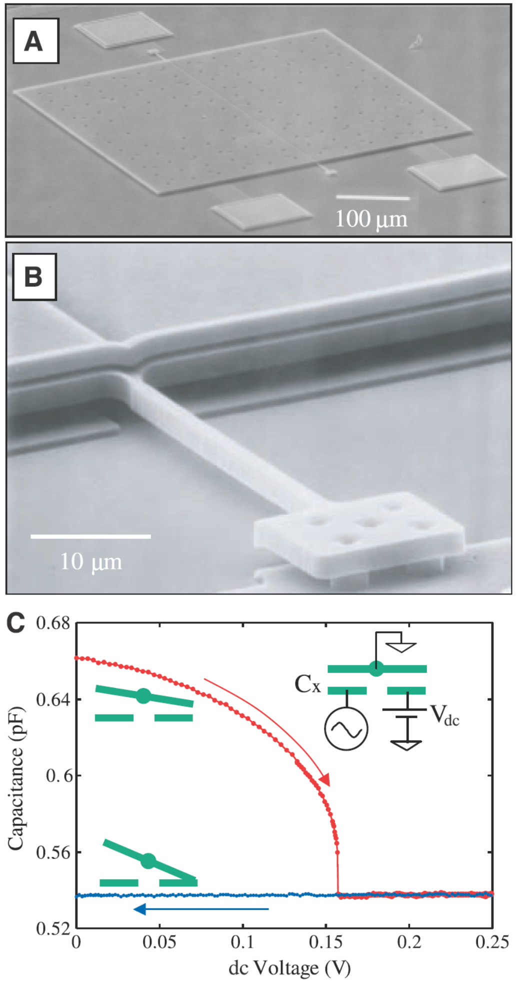


Fig. 1. Scanning electron micrographs of (**A**) the micromachined torsional device and (**B**) a close-up of one of the torsional rods anchored to the substrate. The fixed electrodes are connected by polysilicon lines to the two wire-bonding pads at the bottom of (A), whereas the top plate is connected by one of the torsional rods to the bond pad at the top of (A). (**C**) The capacitance C_x between the top plate and the left electrode as a function of dc voltage V_{dc} applied to the electrode on the right. The inset (top right) is a cross-section schematic of the device (not to scale) with the electrical connections.

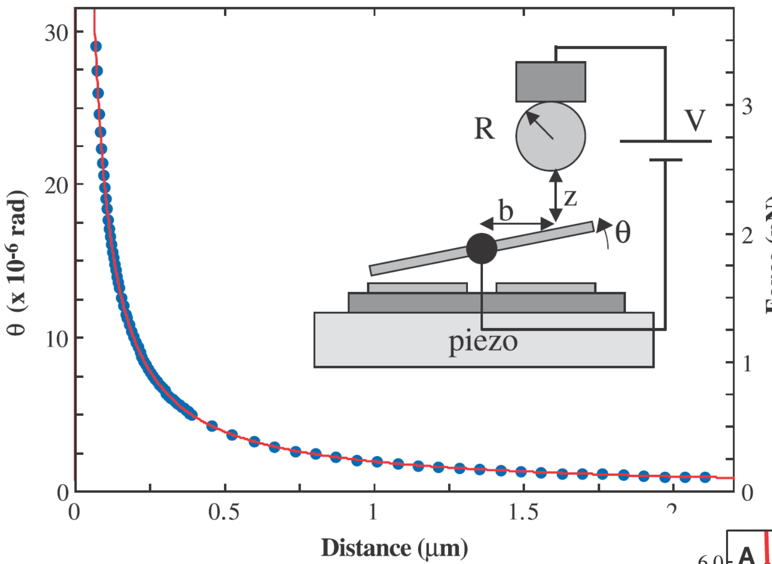
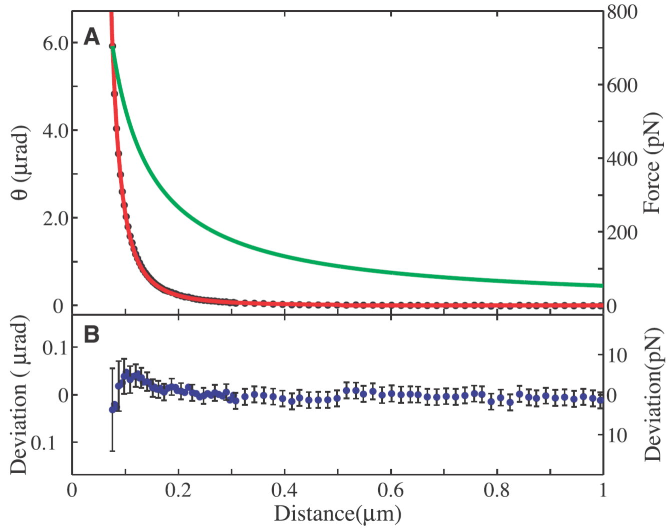


Fig. 2. Angle of rotation θ of the top plate and the attractive electrostatic force as a function of distance (*23*). The red line is a fit obtained with Eq. 7. The voltage *V* applied to the sphere is 289 mV. (Inset) Schematic of the experiment (not to scale).



Demonstration of the Difference in the Casimir Force for Samples with Different Charge-Carrier Densities

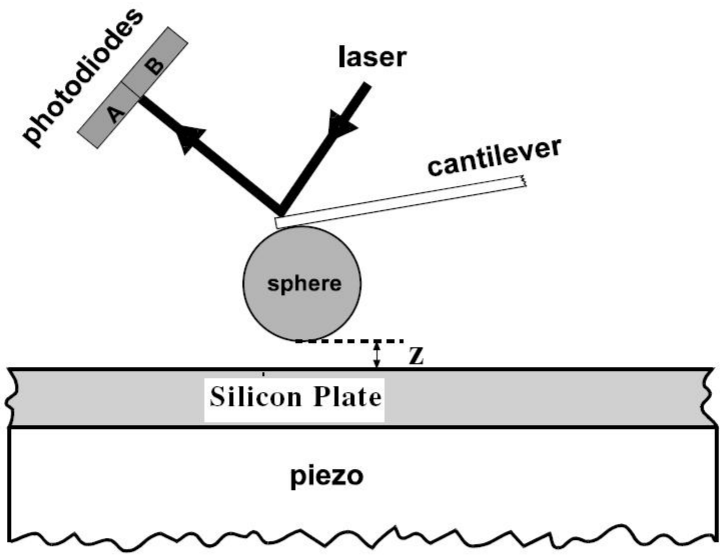
F. Chen,[1] G. L. Klimchitskaya,[2] V. M. Mostepanenko,[3] and U. Mohideen[1]

[1]*Department of Physics, University of California, Riverside, California 92521, USA*
[2]*North-West Technical University, Millionnaya St. 5, St. Petersburg, 191065, Russia*
[3]*Noncommercial Partnership "Scientific Instruments", Tverskaya St. 11, Moscow, 103905, Russia*

(Received 24 May 2006; published 24 October 2006)

A measurement of the Casimir force between a gold coated sphere and two Si plates of different carrier densities is performed using a high vacuum based atomic force microscope. The results are compared with the Lifshitz theory and good agreement is found. Our experiment demonstrates that by changing the carrier density of the semiconductor plate by several orders of magnitude it is possible to modify the Casimir interaction. This result may find applications in nanotechnology.

DOI: 10.1103/PhysRevLett.97.170402 PACS numbers: 12.20.Fv, 12.20.Ds, 68.37.Ps, 73.25.+i

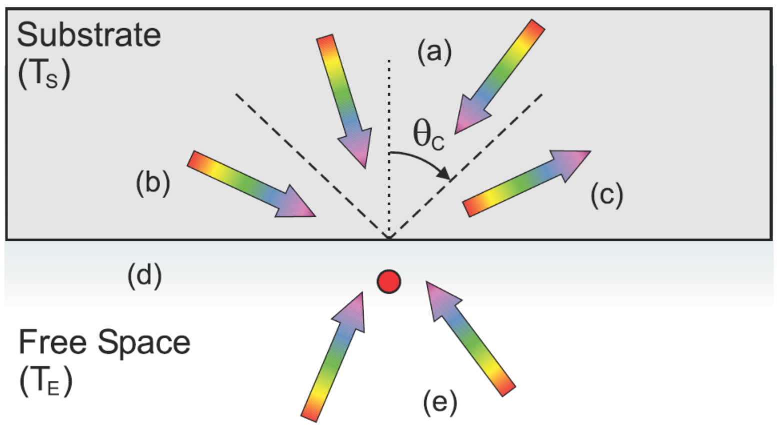


Measurement of the Temperature Dependence of the Casimir-Polder Force

J. M. Obrecht,[1,*] R. J. Wild,[1] M. Antezza,[2] L. P. Pitaevskii,[2,3] S. Stringari,[2] and E. A. Cornell[1,†]
[1]JILA, National Institute of Standards and Technology and University of Colorado, Boulder, Colorado 80309-0440, USA, and Department of Physics, University of Colorado, Boulder, Colorado 80309-0390, USA
[2]Dipartimento di Fisica, Università di Trento and CNR-INFM BEC Center, Via Sommarive 14, I-38050 Povo, Trento, Italy
[3]Kapitza Institute for Physical Problems, ulitza Kosygina 2, 119334 Moscow, Russia
(Received 1 August 2006; published 8 February 2007)

We report on the first measurement of a temperature dependence of the Casimir-Polder force. This measurement was obtained by positioning a nearly pure ^{87}Rb Bose-Einstein condensate a few microns from a dielectric substrate and exciting its dipole oscillation. Changes in the collective oscillation frequency of the magnetically trapped atoms result from spatial variations in the surface-atom force. In our experiment, the dielectric substrate is heated up to 605 K, while the surrounding environment is kept near room temperature (310 K). The effect of the Casimir-Polder force is measured to be nearly 3 times larger for a 605 K substrate than for a room-temperature substrate, showing a clear temperature dependence in agreement with theory.

DOI: 10.1103/PhysRevLett.98.063201 PACS numbers: 34.50.Dy, 03.75.Kk, 31.30.Jv, 42.50.Nn



Exercises

1. Calculate the volume required to make the vacuum field magnitude equal to 1V/m for a wavelength of (a) 1 μm and (b) 100 nm.

2. Show that the time-averaged energy in the electric and magnetic fields of an electromagnetic wave are identical.

3. Calculate the Casimir force between two conducting plates of area 1 cm^2 separated by (a) 1mm and (b) 1μm.

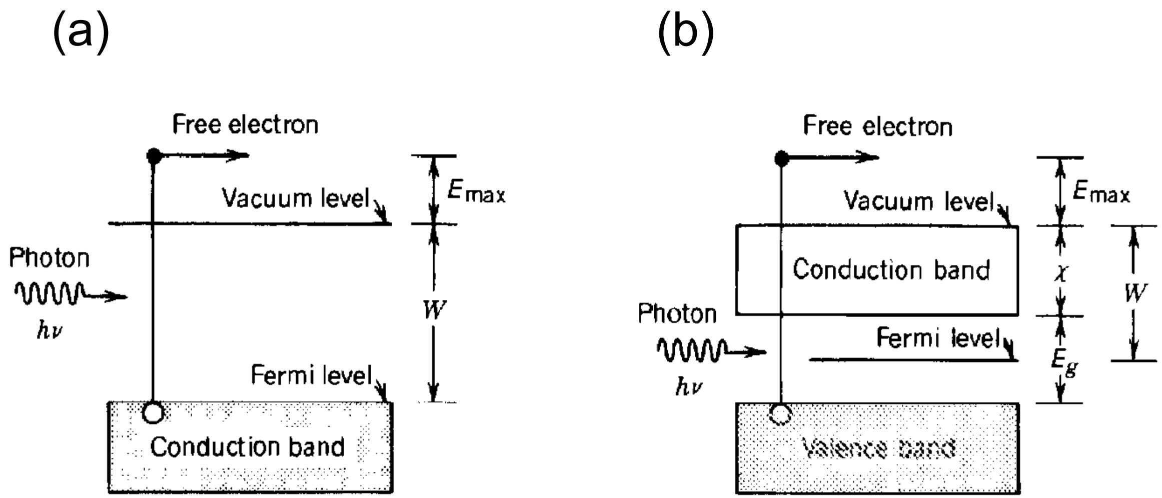
Photodetection

Classes of photodetectors

Thermal detectors: photon energy converted into heat

Photoelectric detectors: photon energy converted into mobile charge carries to yield electric current

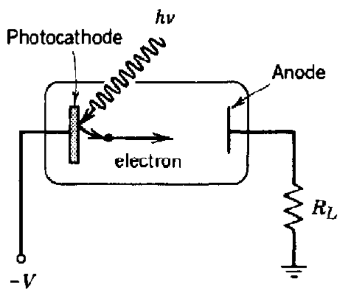
External photoeffect: photoelectric emission



Photoelectric emission from (a) a metal and (b) a semiconductor

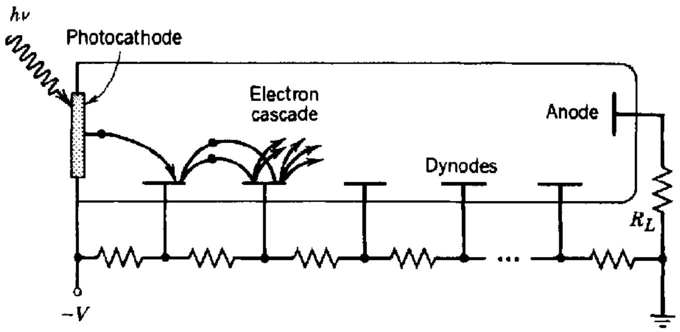
Photodetectors based on photoelectric emission

Phototube



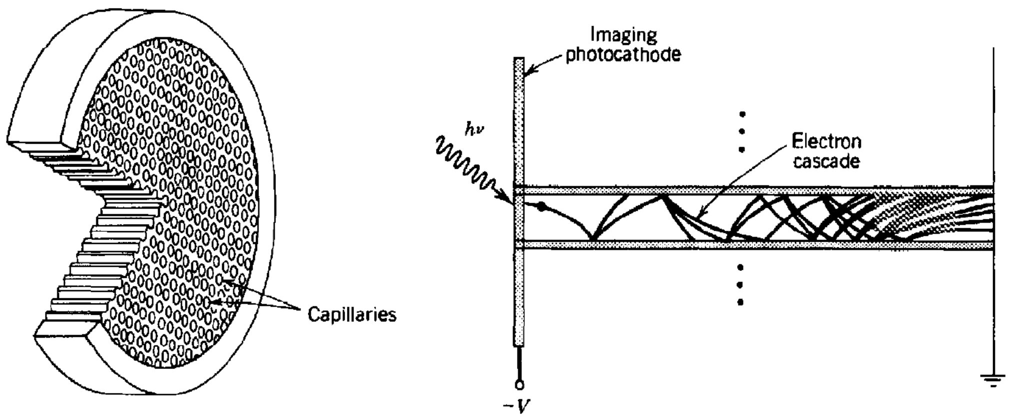
(a)

Photomultiplier tube (PMT)

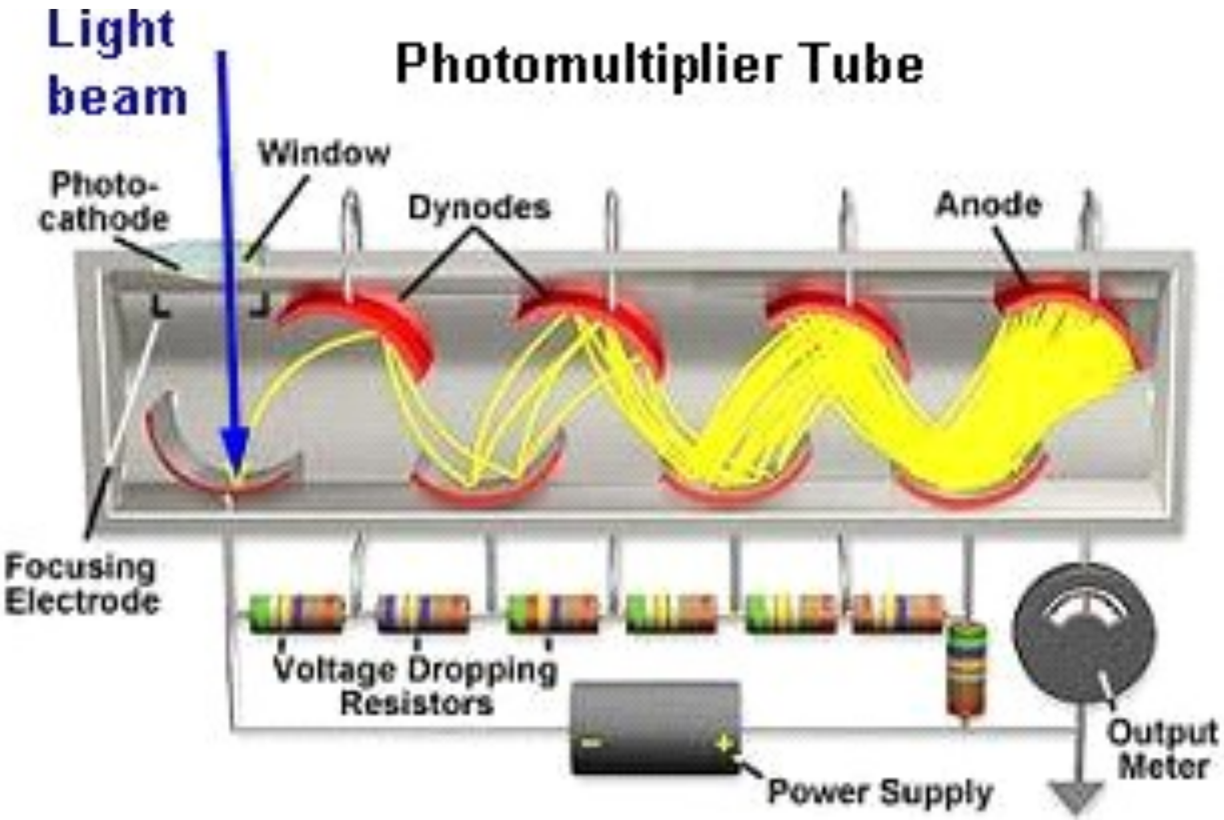


(b)

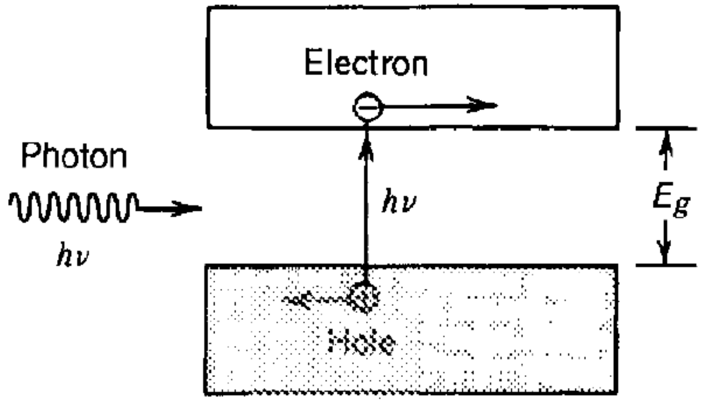
Microchannel plate



Photomultiplier tubes (PMTs)



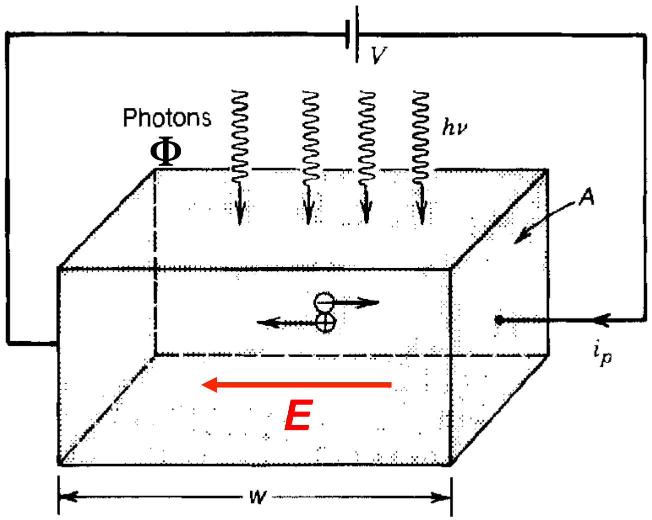
Internal photoeffect: photoconductivity



electron-hole photogeneration in a semiconductor

Photoconductor detectors

biased photoconductor detector



Φ = photon flux (photons/s)

i_p = photocurrent (A)

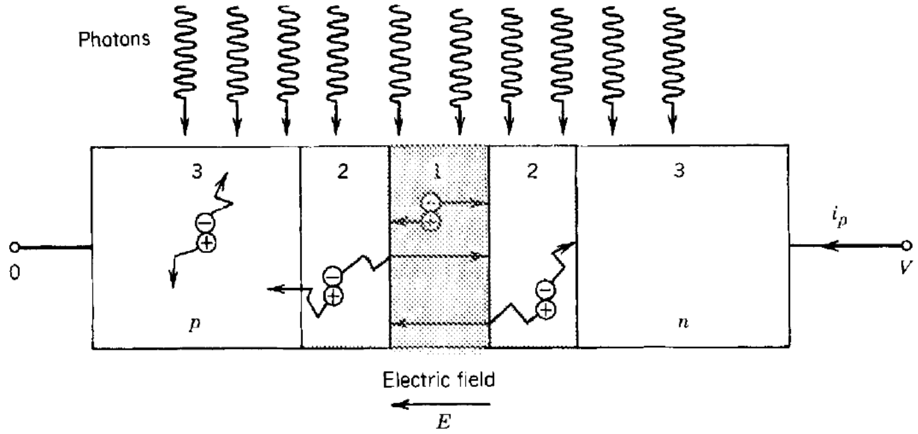
$$v_{e(h)} = \mu_{e(h)} E$$

$$i_p \propto \Phi$$

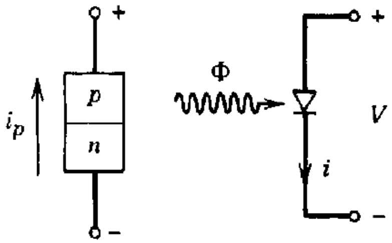
each carrier pair generates in the external circuit an electric pulse of area *e*

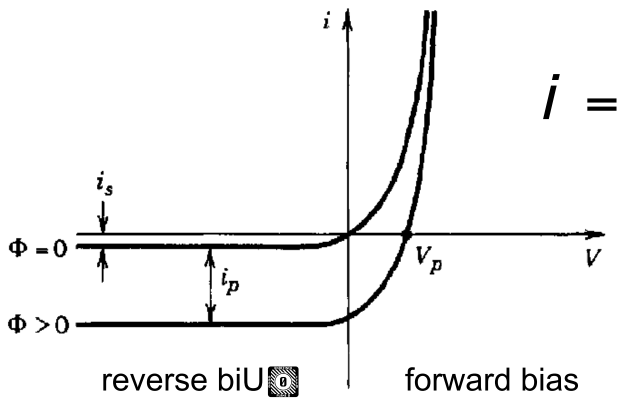
The *p-n* photodiode

Electron-hole pair generation in a p-n photodiode



i-V characteristics

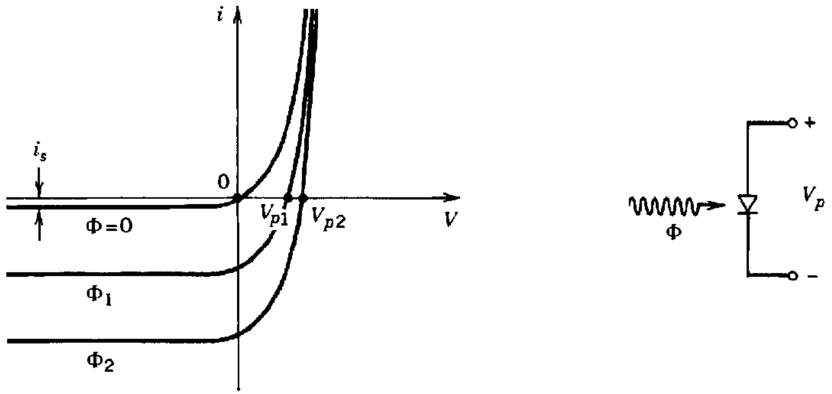




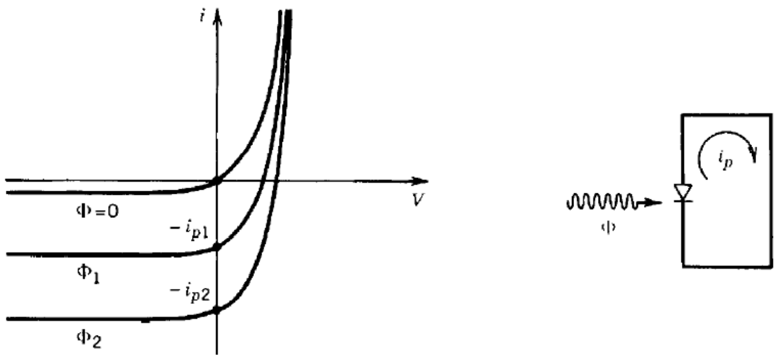
$$i = i_s \cdot \left[\exp\left(\frac{eV}{k_B T} \right) - 1 \right] - i_p$$

Operation of a *p-n* photodiode

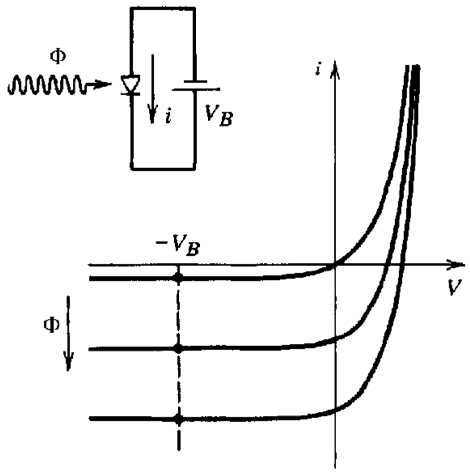
*(i) open-circuit (**photovoltaic**) operation*



(ii) short-circuit operation

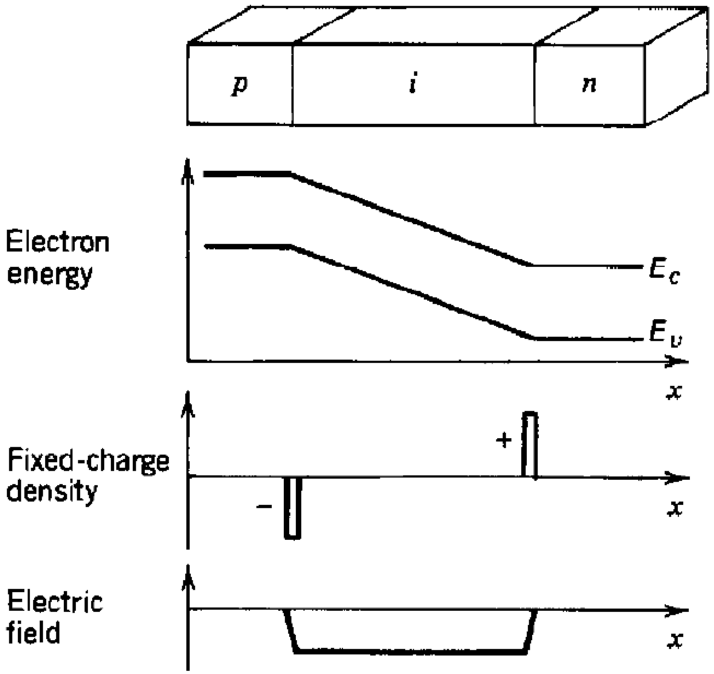


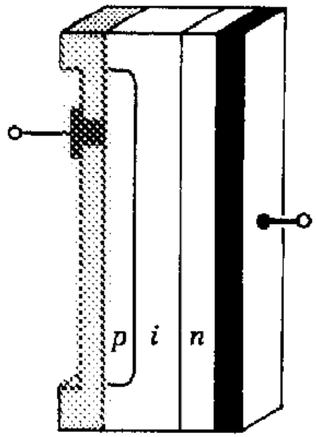
*(iii) reverse-bias (**photoconductive**) operation*



The *p-i-n* photodiode

Intrinsic (lightly doped) layer sandwitched between the *n* and *p* layers

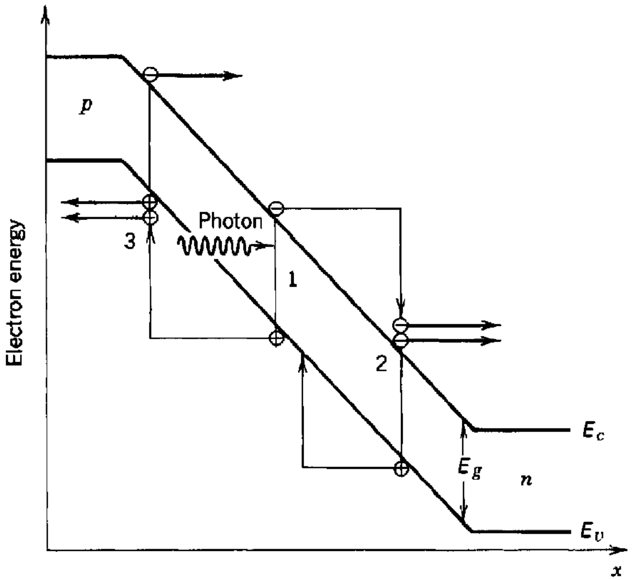


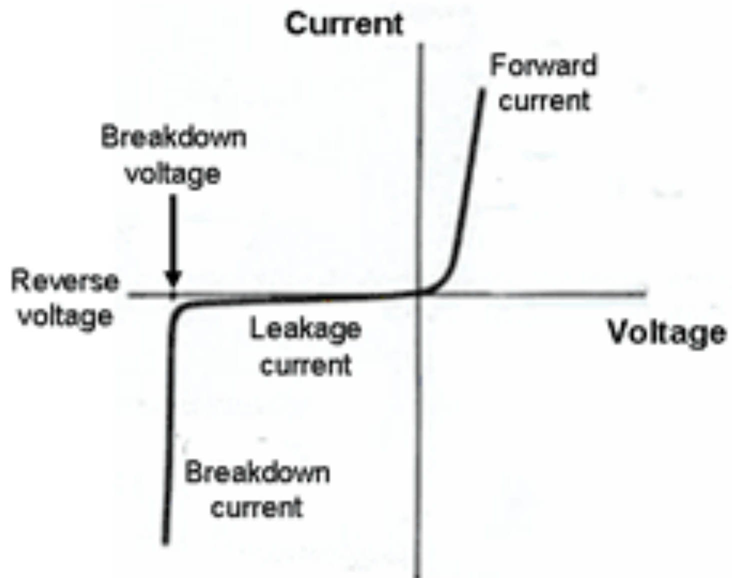


Heterostructure devices: AlGaAs/GaAs, InGaAs/InP, HgCdTe/CdTe …

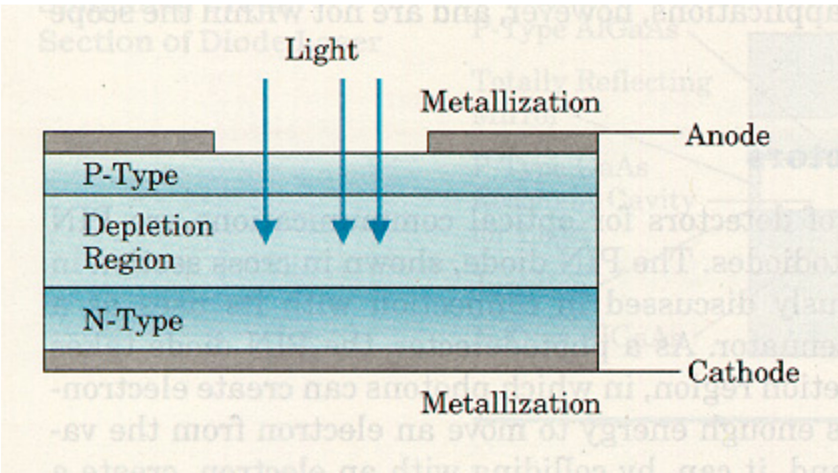
Avalanche photodiodes (APDs)

An avalanche photodiode (APD) converts each detected photon into a cascade of moving carrier pairs by *impact ionization*





Zener Diode Characteristic



Properties of semiconductor photodetectors

- Quantum efficiency
- Responsivity
- Gain
- Response time

Quantum efficiency

Probability that a single photon incident on the device generates a photocarrier pair that contribute to the detector current

$$\eta = (1 - R)\xi\left[1 - \exp(-\alpha d)\right]$$

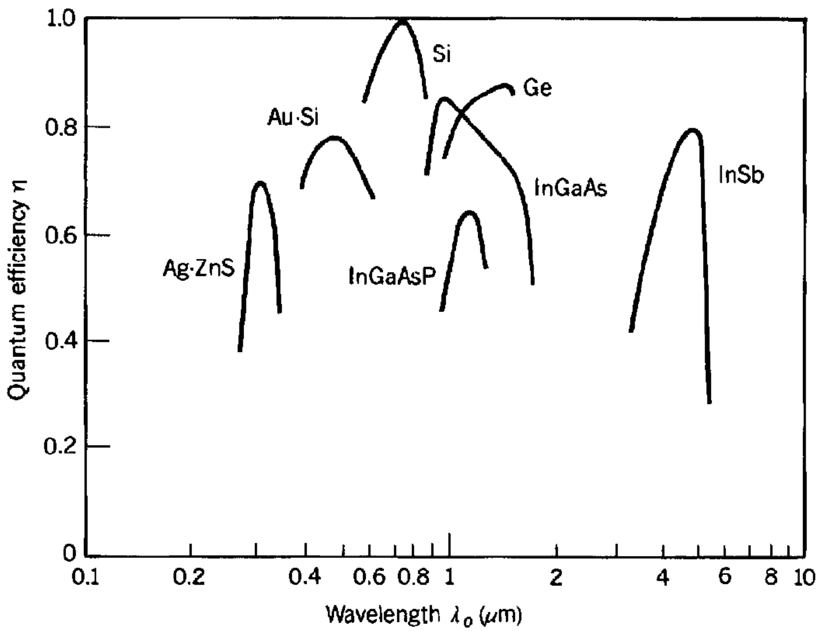
R = optical reflectance at the surface

ξ = e-h fraction contributing to the detector current

α = absorption coefficient of the material

d = photodetector depth

Quantum efficiency vs. wavelength for various photodiodes



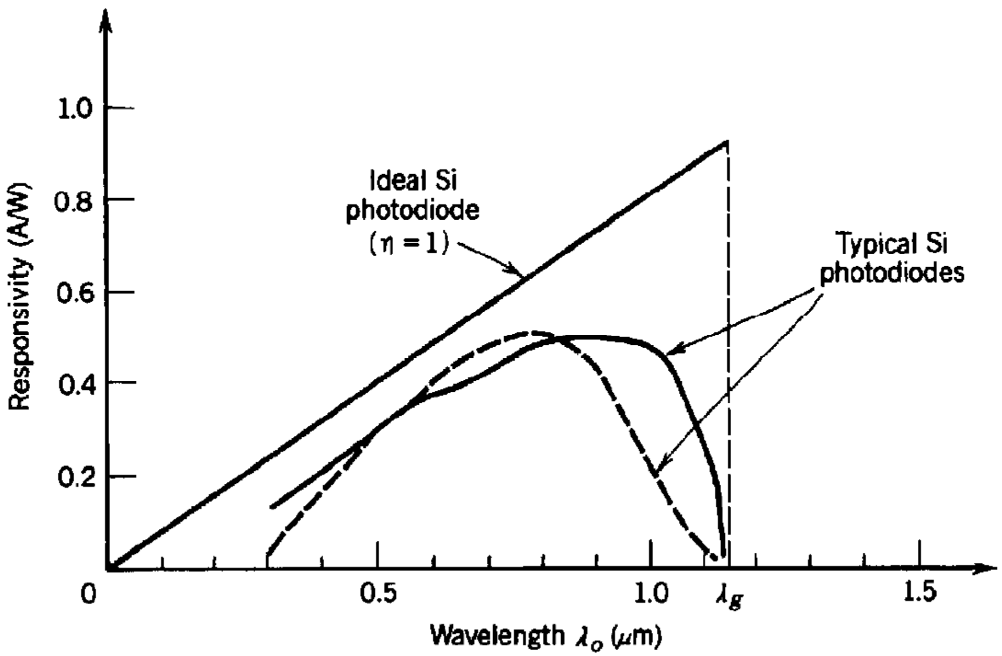
Responsivity

Relates the electric current (i_p) flowing in the device to the incident optical power (P)

$$i_p = \eta \frac{eP}{h\nu} = \Re P \quad \Longrightarrow \quad \Re = \eta \frac{e}{h\nu} = \eta \frac{e\lambda_0}{hc} \quad \left(\frac{\text{A}}{\text{W}}\right)$$

P = incident optical power

$h\nu$ = photon energy

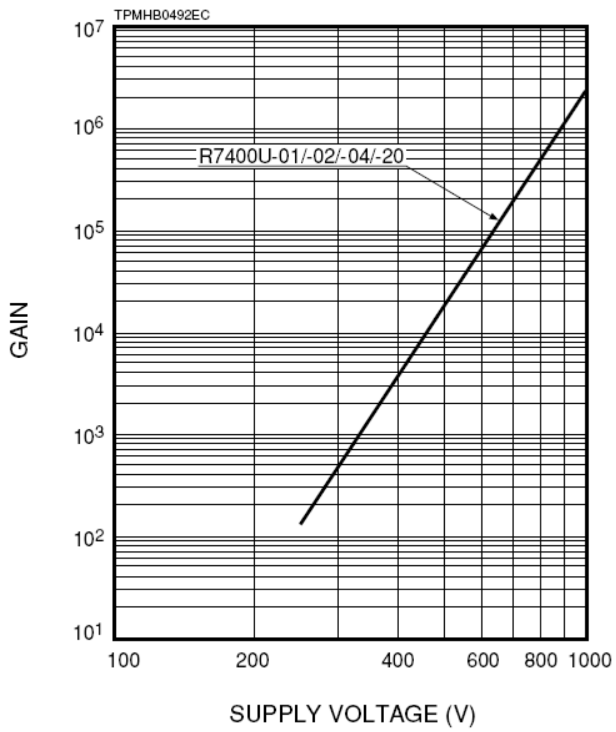


Device with gain

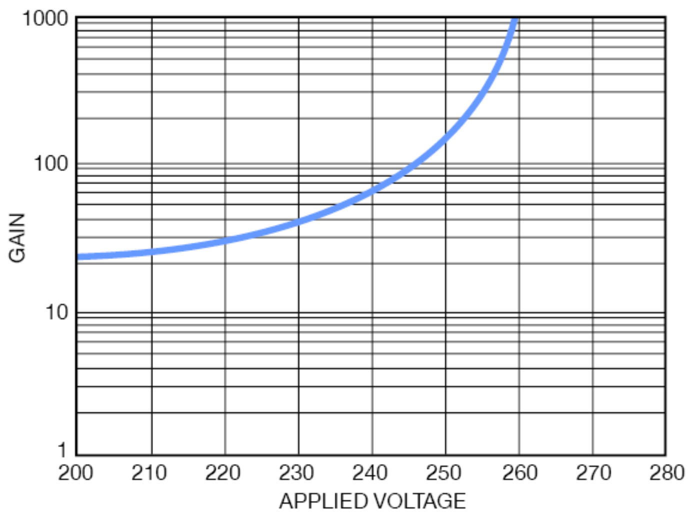
Each carrier pair produces in the external circuit a current pulse of charge $q > e$:

$$G = \frac{q}{e} \quad \Longrightarrow \quad \Re = G\eta \frac{e\lambda_0}{hc}$$

PMT (G: $10^2 \div 10^8$)



APD (G: $1 \div 1000$)

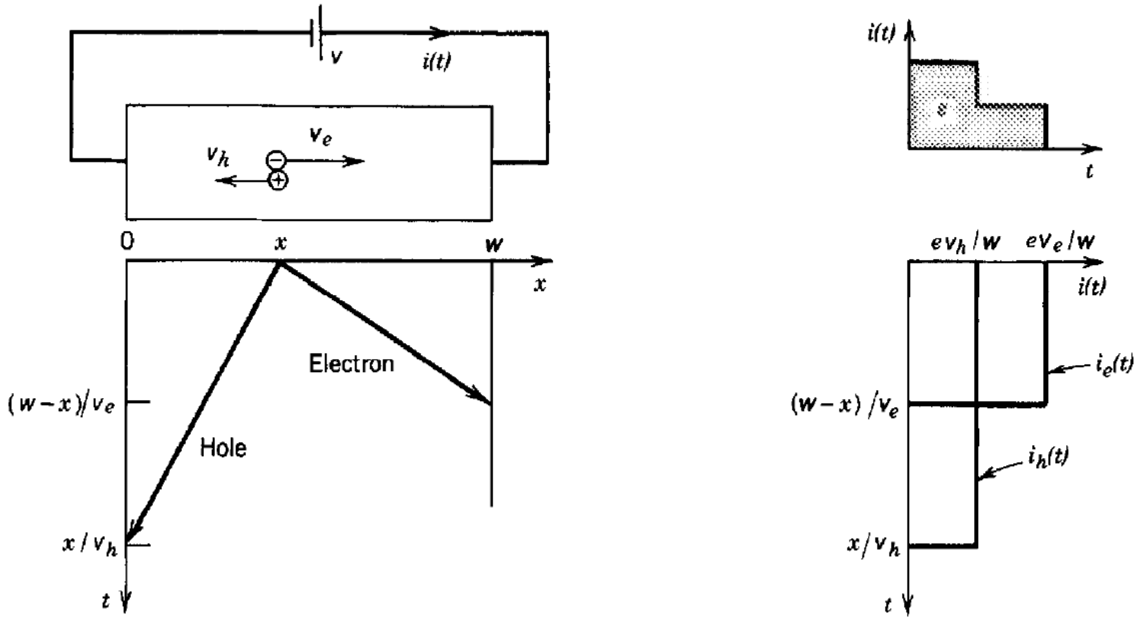


Response time

Charge delivered to the external circuit by carrier motion occupies an extended time

$$t_{e(h)} = \frac{w}{v_{e(h)}}$$

transit time



Impulse-response function determined by convolving *i*(*t*) with time-constant spread function *f*(t):

$$f(t) = \frac{1}{RC}\exp(-\frac{t}{RC})$$