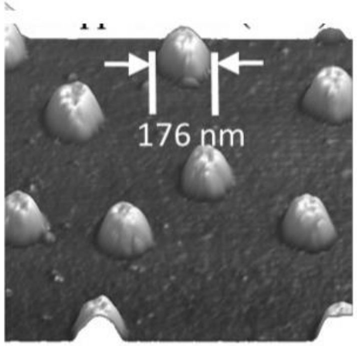
Nanostructures: from sensors to quantum tunneling devices ….

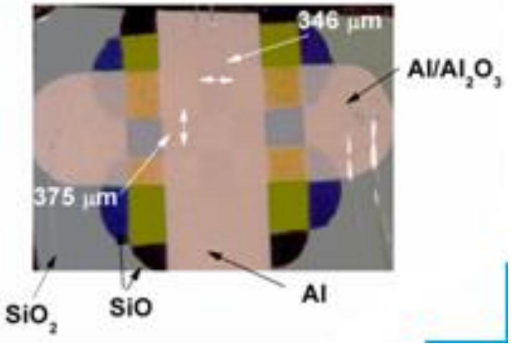
Edgar J. Patiño

Universidad de los Andes (Physics)– Bogotá Colombia

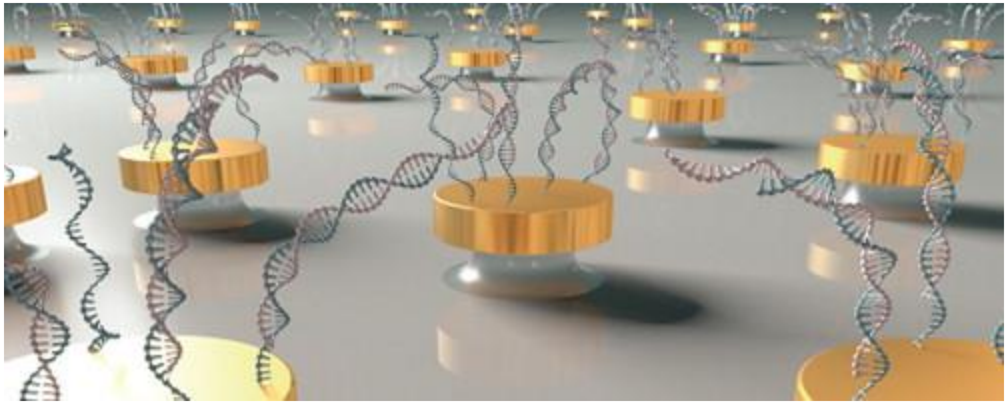
Plasmonic sensors



Quantum Tunneling



Plasmon resonances in nano structures ……



César Aurelio Herreño-Fierro (PhD student)
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Departamento de Física
Universidad de los Andes

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Gaspar Armelles
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Instituto de Microelectrónica de Madrid –
Centro Nacional de Microelectrónica (CSIC)

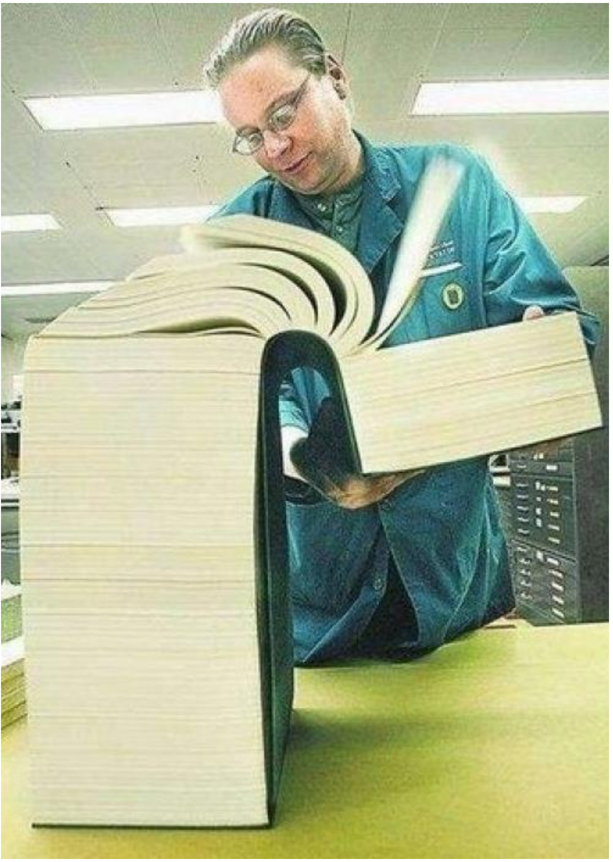
M.-Carmen Estevez, *et. al.* Analytica Chimica Acta, 806, 55-73 (2014)

During this talk…..

- Motivation - > Why is it important why should we care about "plasmons" -> magnetic response?
- Plasmon resonance and Magnetic optic Kerr Effect (MOKE) as separate effects
- What happens with MOKE when plasmons are present? ->magneto plasmons TMOKE experiments
- Conclusions

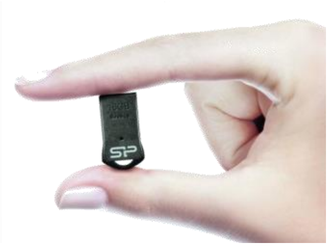
Motivation

The storage and speed problem.



~ 125 x 14000-pages-books

→8Gb



~ 125 x 8Gb-flash-memories

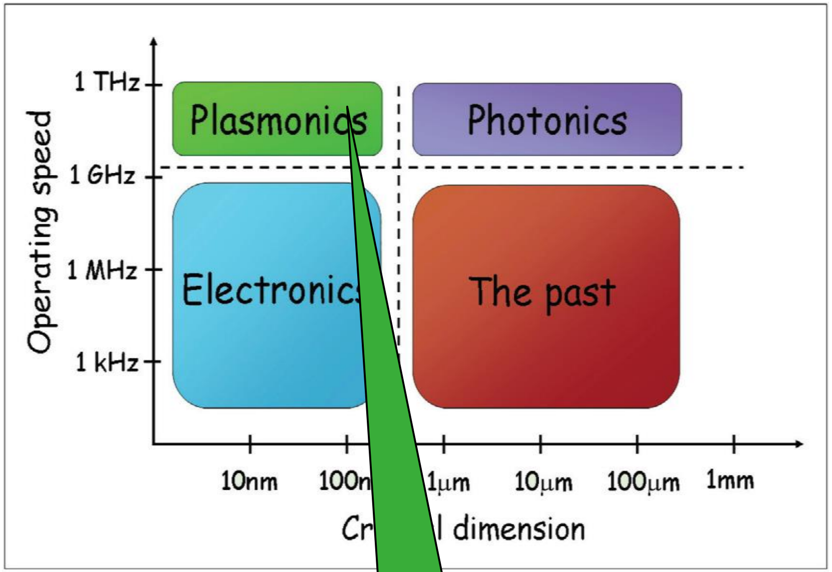
-> 1 second

photonics - speed

14000 pages → 70Mb

Speed vs Storage

Operation Speed



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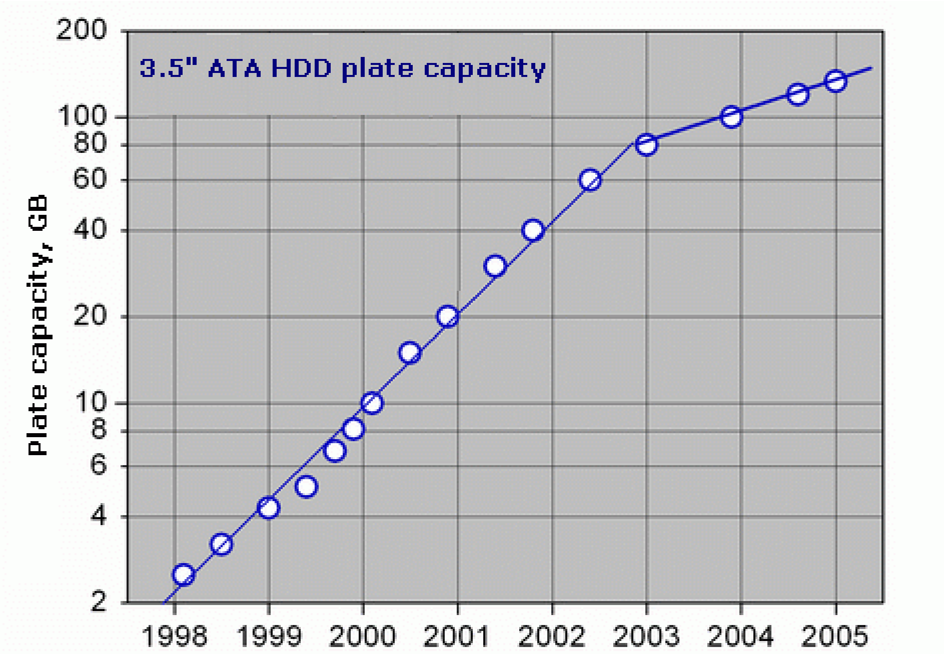
Crecimiento capacidad de los discos duros



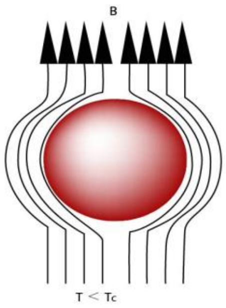
http://ixbtlabs.com/articles2/digests/hdd2k4.html

Pasive Devices

Active Devices

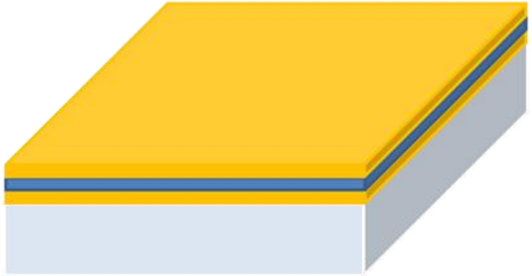
Wave guides, resonators, interferometers etc.

Switches, transistors, detectors, logic gates etc.

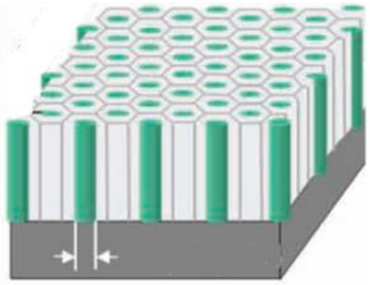


Magnetoplasmons

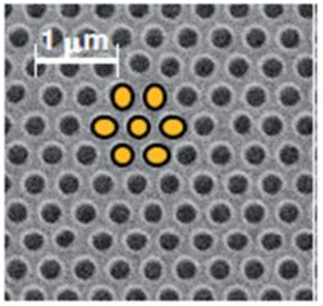
Multilayered [1]
(homogeneous)



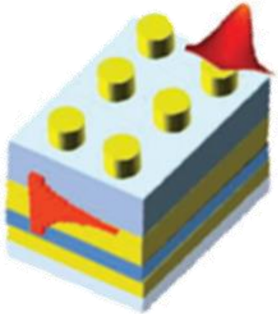
Embedded
nanowires [2]



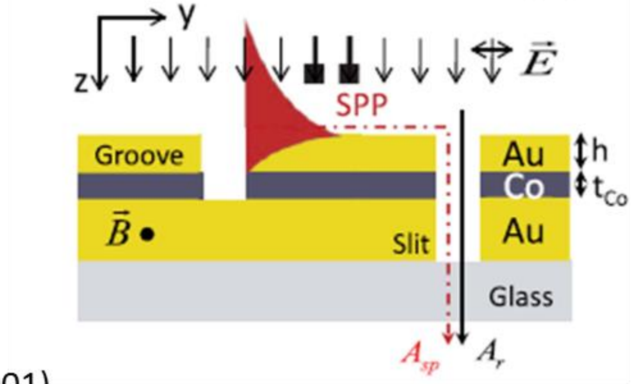
Perforated
membrane [3]



Nanodisks [4]



SPP interferometer [5]



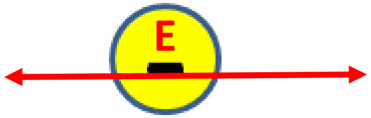
METAL
+
FERROMAGNET

[1] Phys. Rev. B. **64**, 235422 (2001)
[2] Phys. Rev. B. **81**, 054424 (2010)
[3] Phys. Status Solidi RRL **4**, No. 10, 271–273 (2010)
[4] Optics Express, **18**, 15635 (2010)
[5] Phys. Rev. B. **86**, 035118 (2012)
[6] New J. Phys. **15** 075024 (2013)

Magnetoplasmonic materials

Plasmons

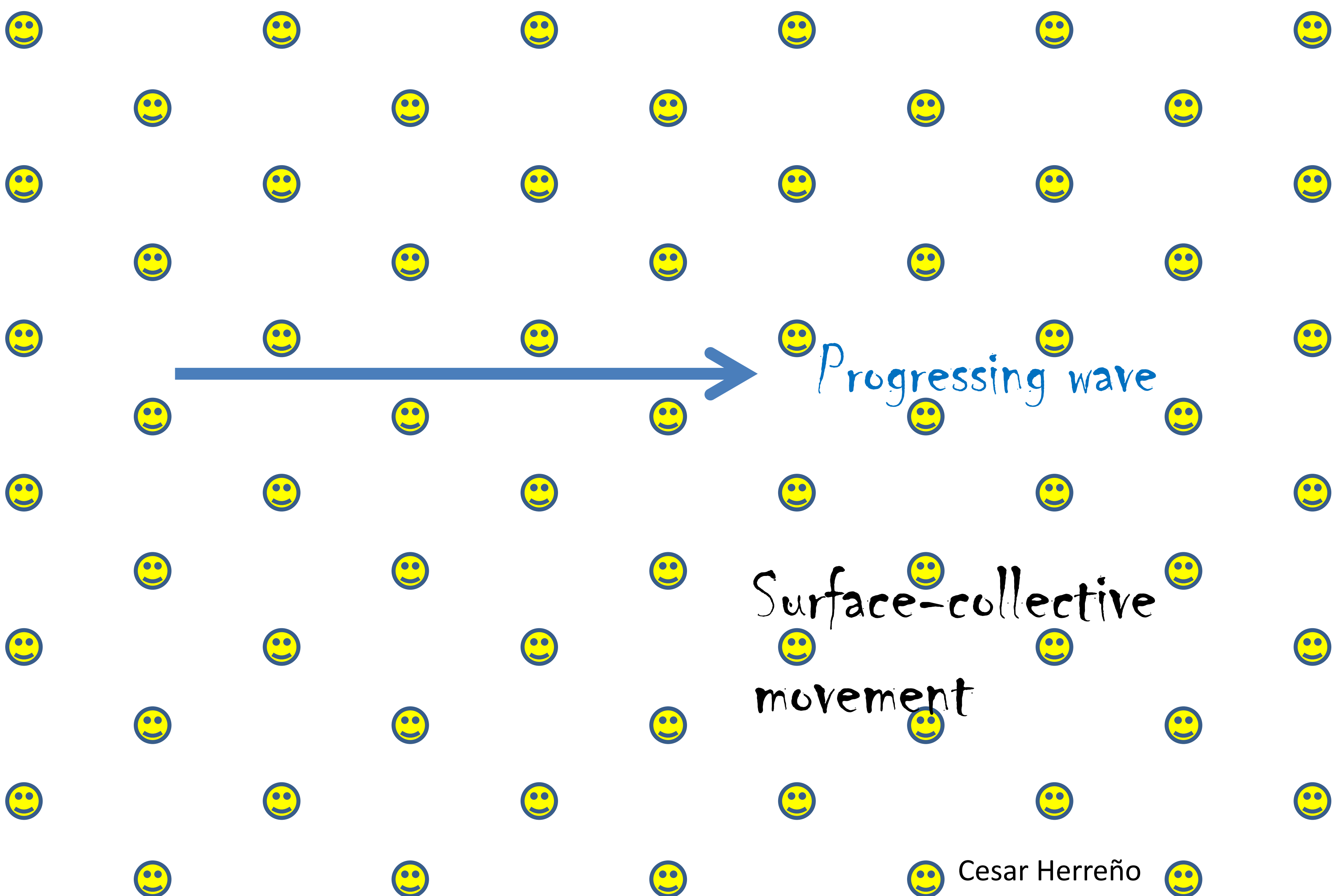
What is a plasmon?



Colective oscillation of a gas of electrons
-> quantum of “electron charge oscillation” **(Plasmon)**

Lycurgus Cup – roman artisans 1600 years ago (IV century). Normally green under external light turns red when illuminated from within. This is the result of plasmon excitation within the glass matrix (nano particles of gold an silver)

http://wiesner.mse.cornell.edu/res_optics.htm

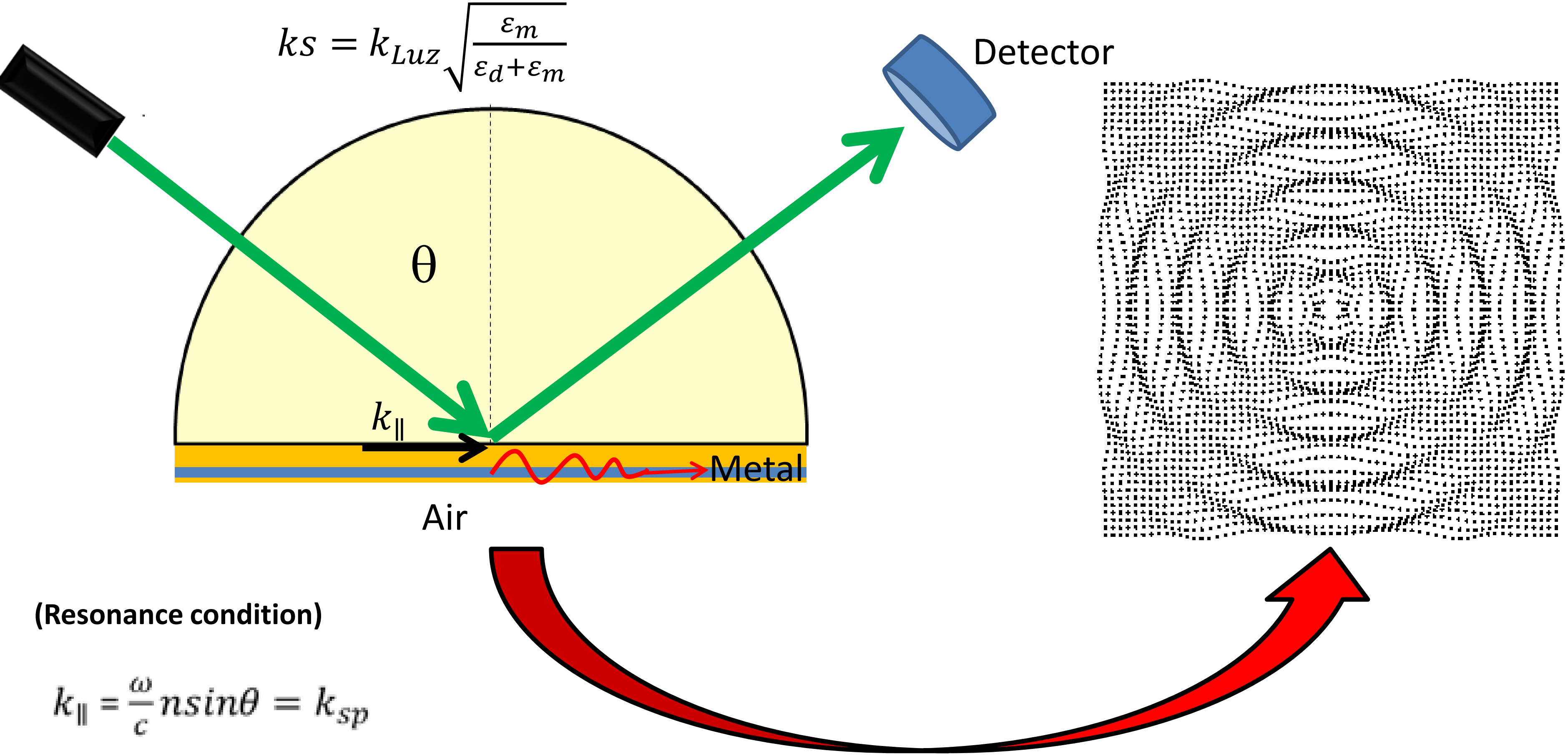


Progressing wave

Surface-collective movement

Cesar Herreño

Surface Plasmon Resonance (SPR)
How plasmons are excited in Kretschmann configuration?



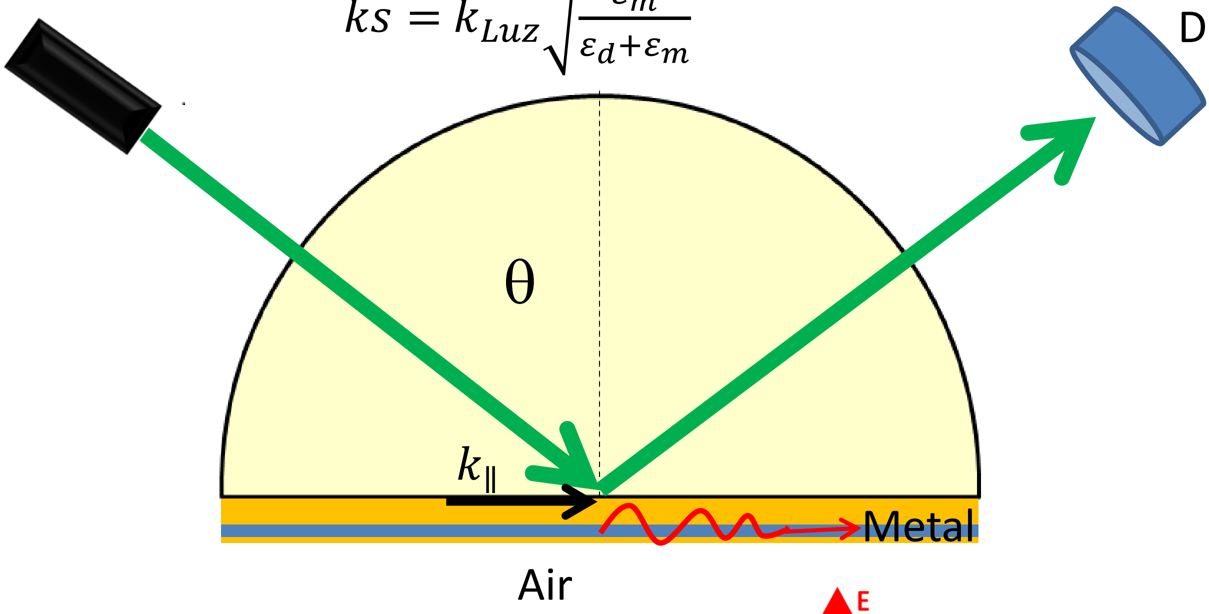
$$ks = k_{Luz}\sqrt{\frac{\varepsilon_m}{\varepsilon_d+\varepsilon_m}}$$

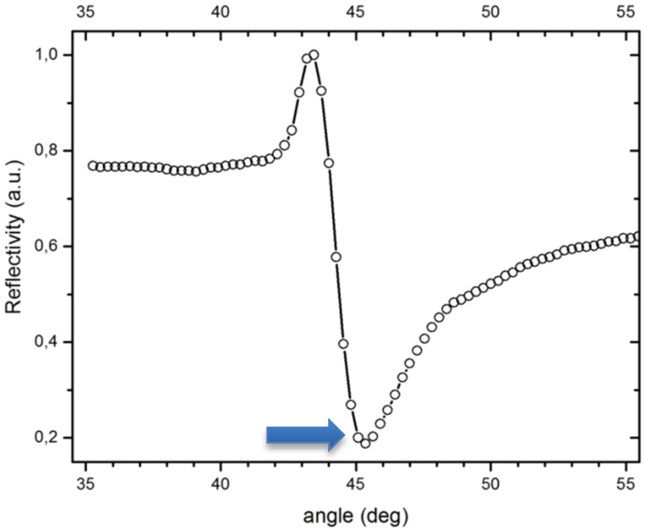
(Resonance condition)

$$k_{\|} = \frac{\omega}{c} n \sin\theta = k_{sp}$$

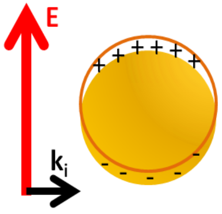
How are plasmons detected ?

$$ks = k_{Luz}\sqrt{\frac{\varepsilon_m}{\varepsilon_d+\varepsilon_m}}$$





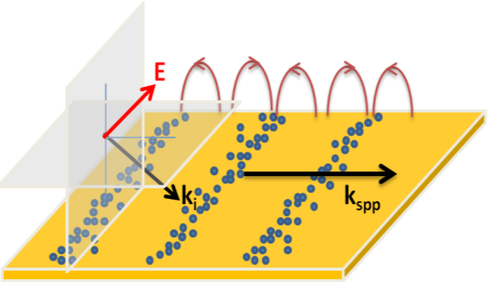
$$k_{\parallel} = \frac{\omega}{c} n\sin\theta = k_{sp}$$ **(Resonance condition)**



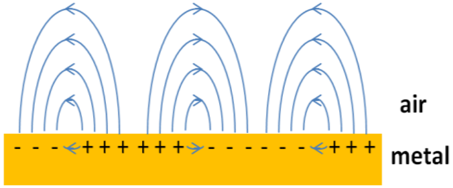
LSP – localized plasmons

frequency matching

Absorption spectrum



Collective charge oscillations at the metal-air(2D) interface in resonance with incident fotons.



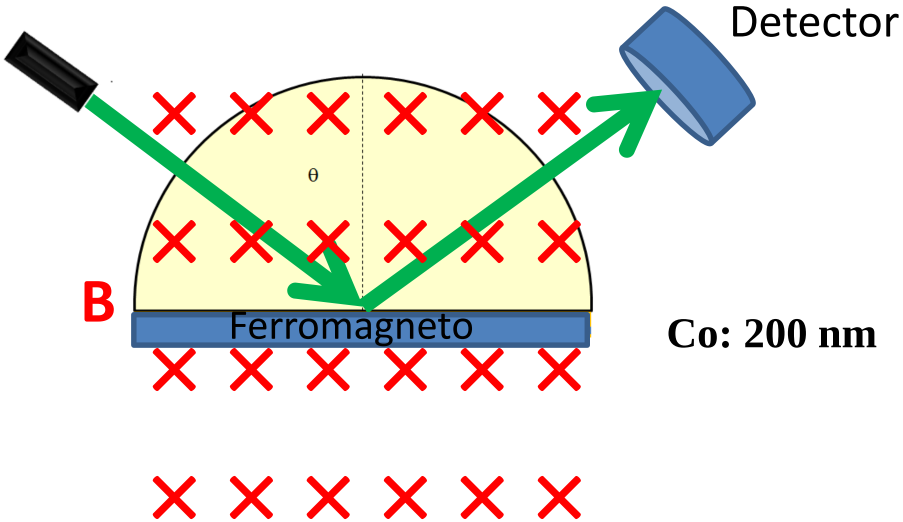
Strong confinement (below wave length)

SPP – Propagating Plasmons

frequency + momentum matching

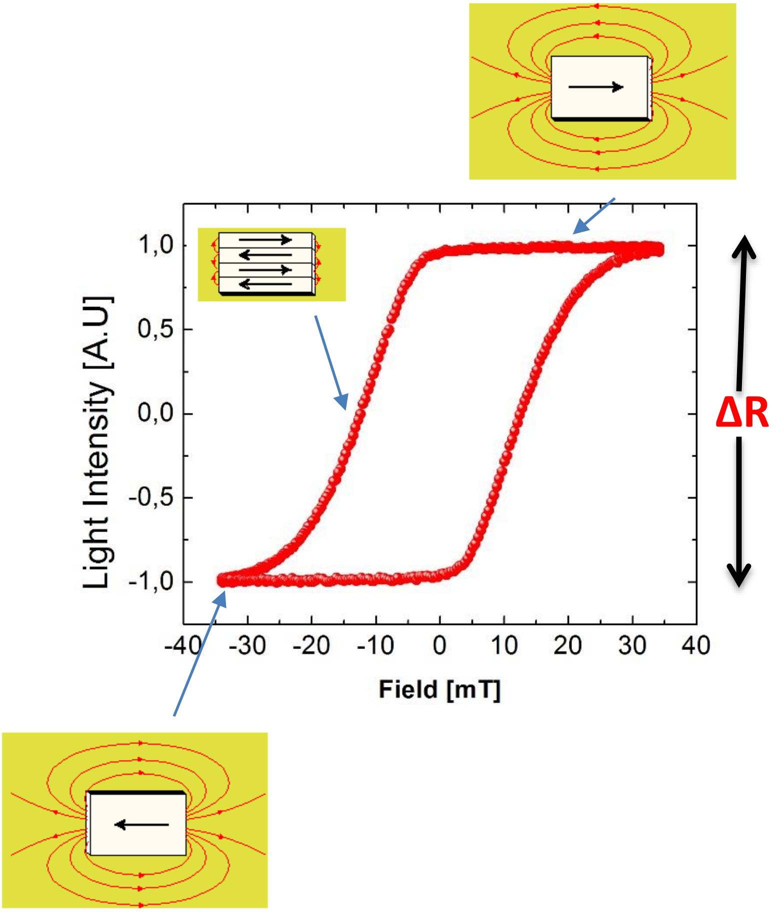
Universidad de los Andes

Magnetic optic Kerr Effect (MOKE)

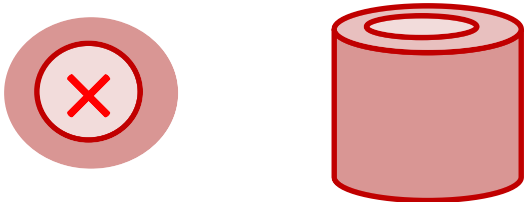


Transversal Configuration.- Reflected light of a magnetic material shows variation in intensity as function of applied magnetic field.

This is due to that the dielectric properties depend on the material´s magnetic moment.



$$\Delta R = R(+M_y^s) - R(-M_y^s)$$

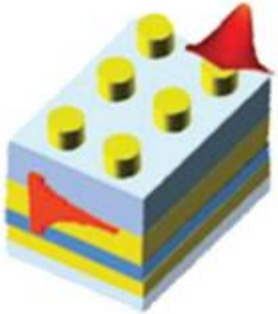


http://www.study-on-line.co.uk/whoami/thesis/chap5.html

What happens with MOKE when plasmons are present?

Multilayered [1]
(homogeneous)

Nanodisks [4]



METAL
+
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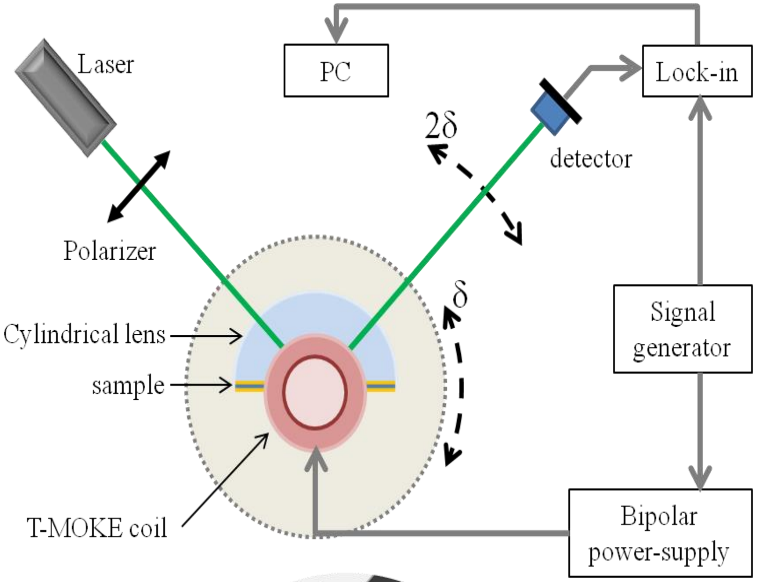
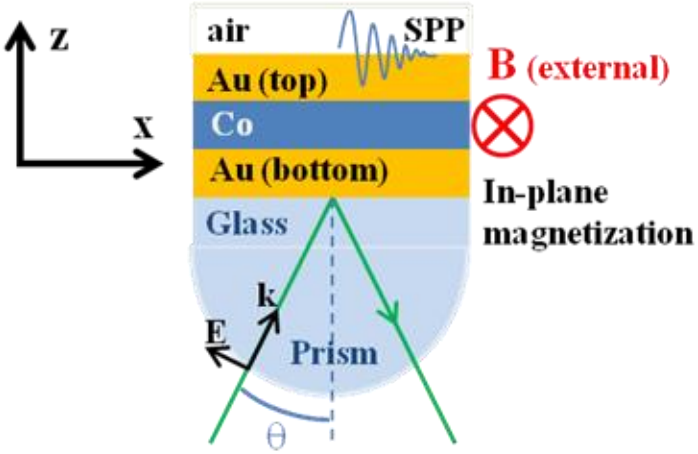
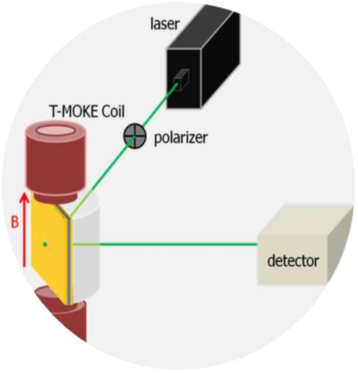
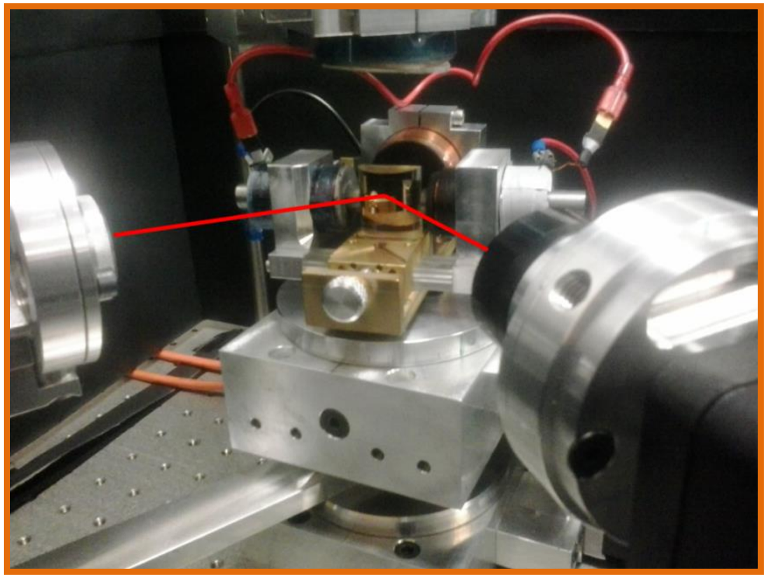
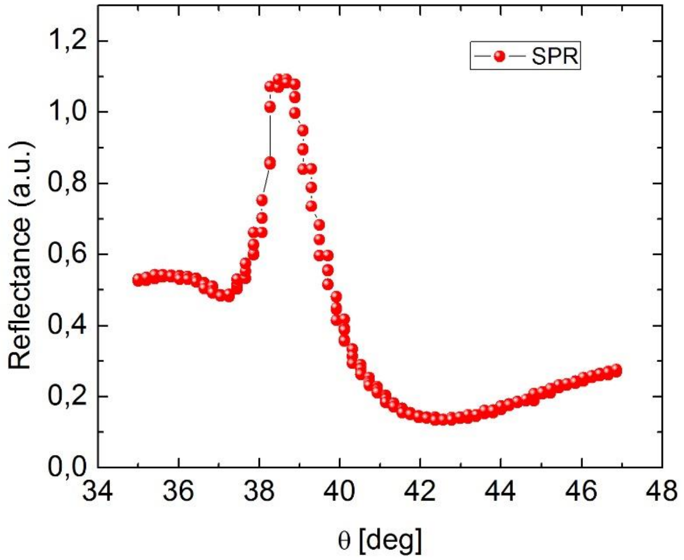
How does the experiment is done?

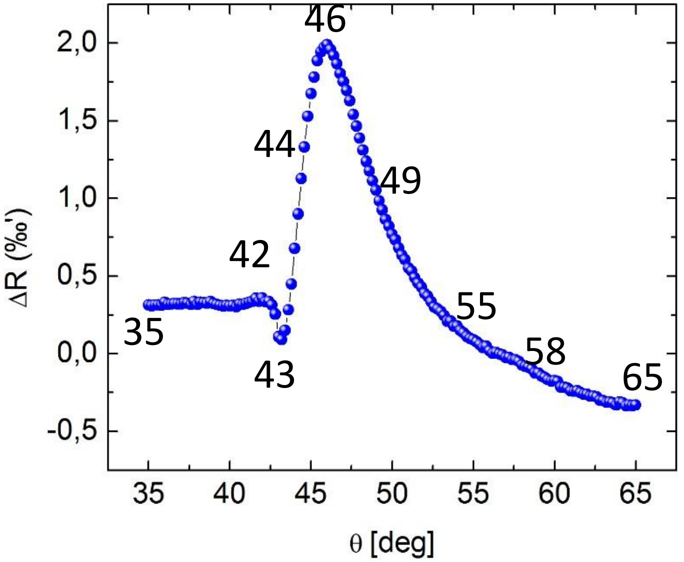


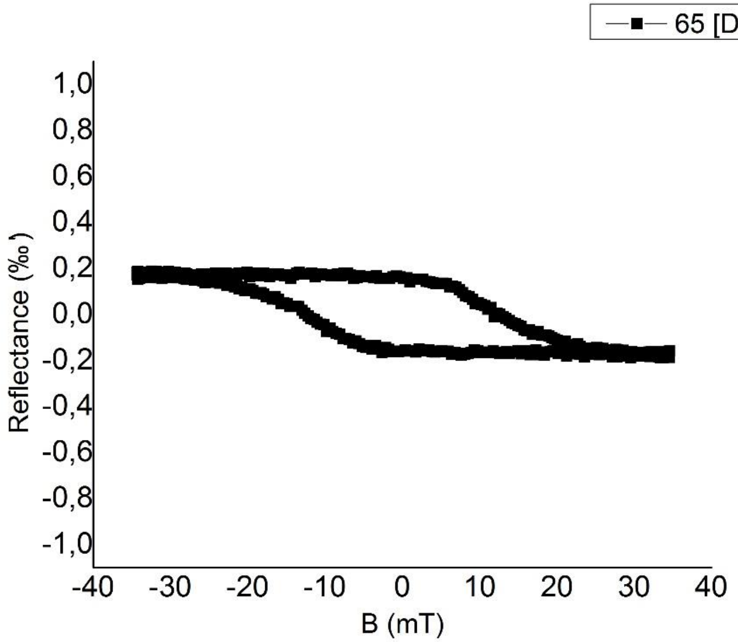




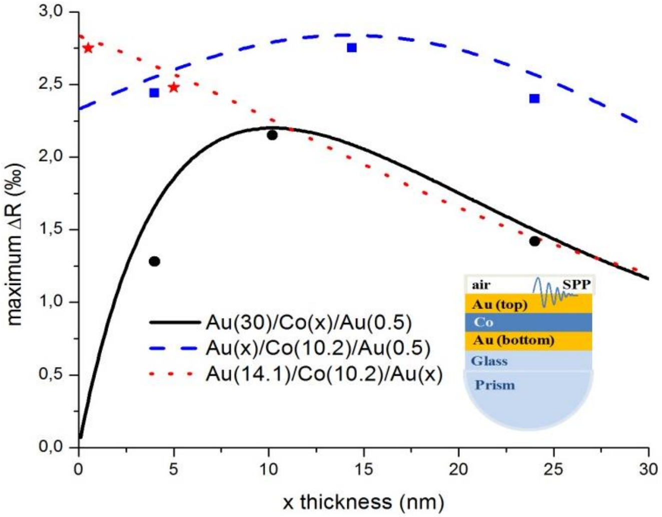


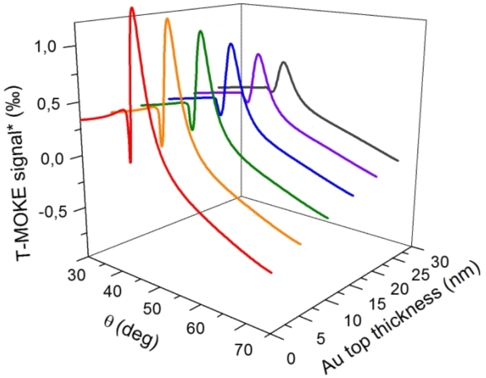

SPR
Reflectance (a.u.)
1,2
1,0
0,8
0,6
0,4
0,2
0,0
34
36
38
40
42
44
46
48
θ [deg]

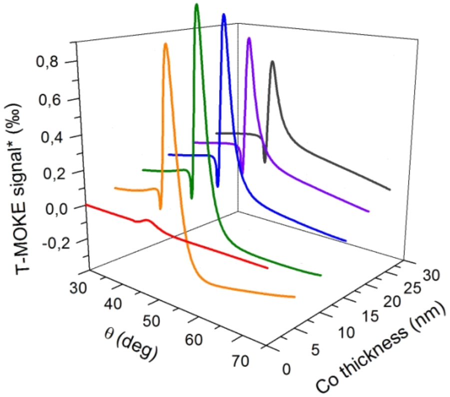

ΔR (‰')
2,0
1,5
1,0
0,5
0,0
-0,5
35
40
45
50
55
60
65
θ [deg]
46
44
49
42
35
43
55
58
65

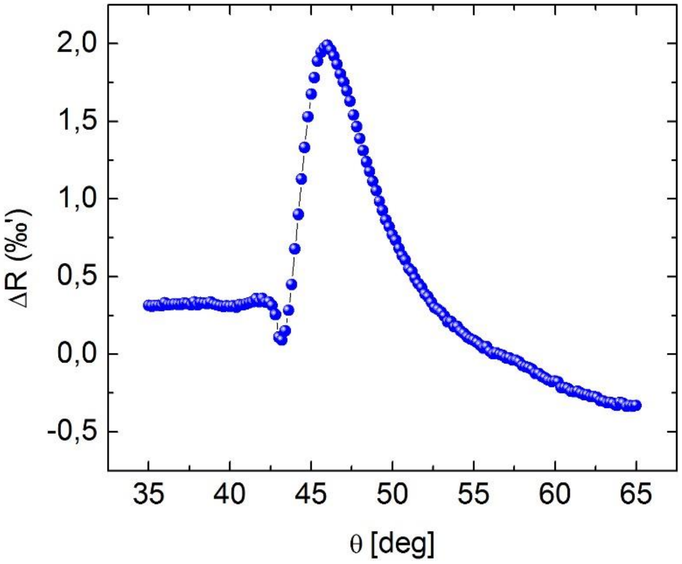

65 [Deg]
Reflectance (‰')
1,0
0,8
0,6
0,4
0,2
0,0
-0,2
-0,4
-0,6
-0,8
-1,0
-40
-30
-20
-10
0
10
20
30
40
B (mT)

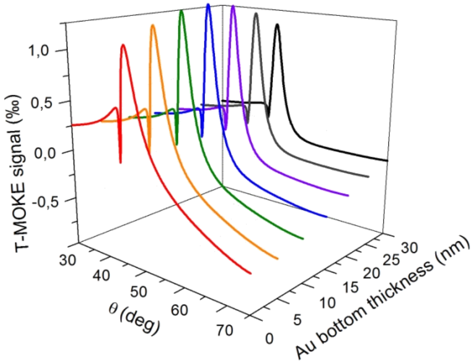
Maximización del efecto MOKE con plasmones







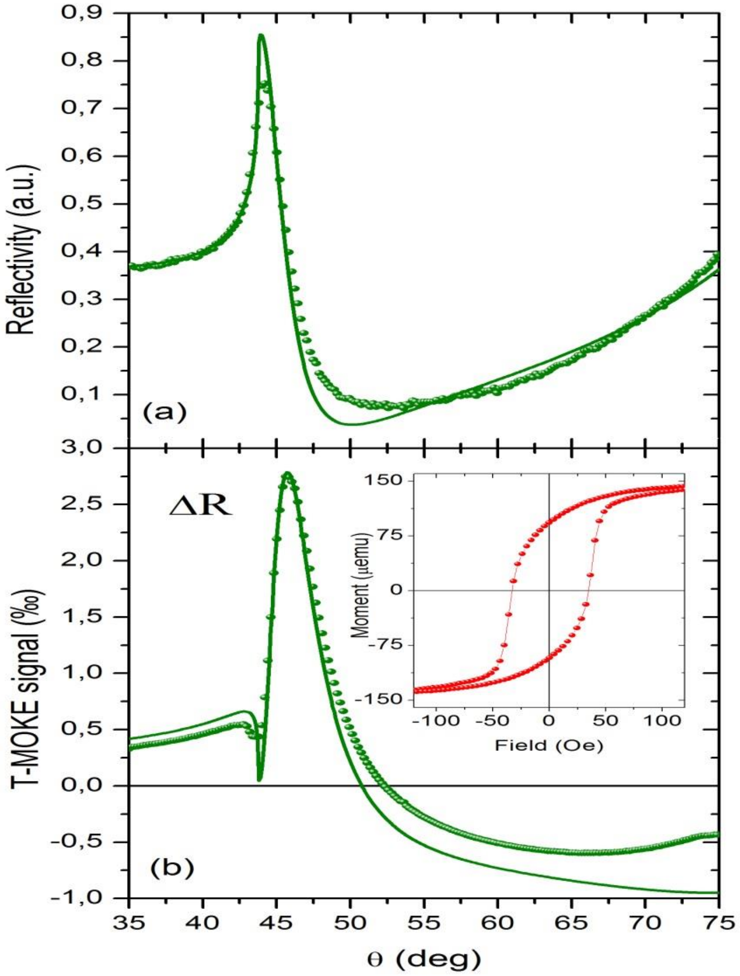


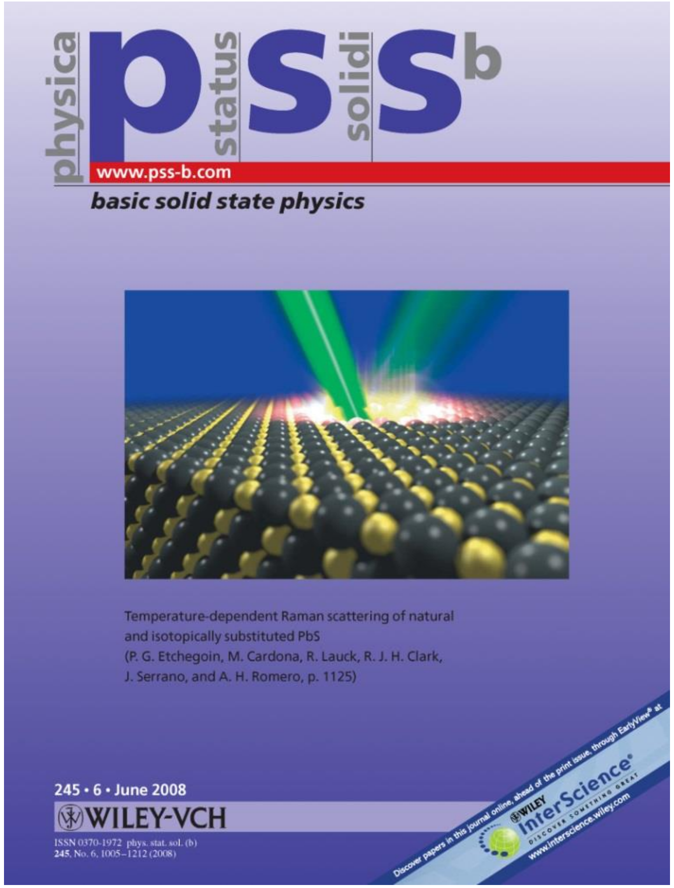


$$\Delta R = R\left(+M_y^s\right) - R\left(-M_y^s\right)$$

Au(14.1)/Co(10.2)/ Au(0.5).

Magnetoplasmones en los Ar

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www.pss-b.com

basic solid state physics

Temperature-dependent Raman scattering of natural and isotopically substituted PbS
(P. G. Etchegoin, M. Cardona, R. Lauck, R. J. H. Clark, J. Serrano, and A. H. Romero, p. 1125)

245 • 6 • June 2008

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ISSN 0370-1972 phys. stat. sol. (b)
245, No. 6, 1005–1212 (2008)

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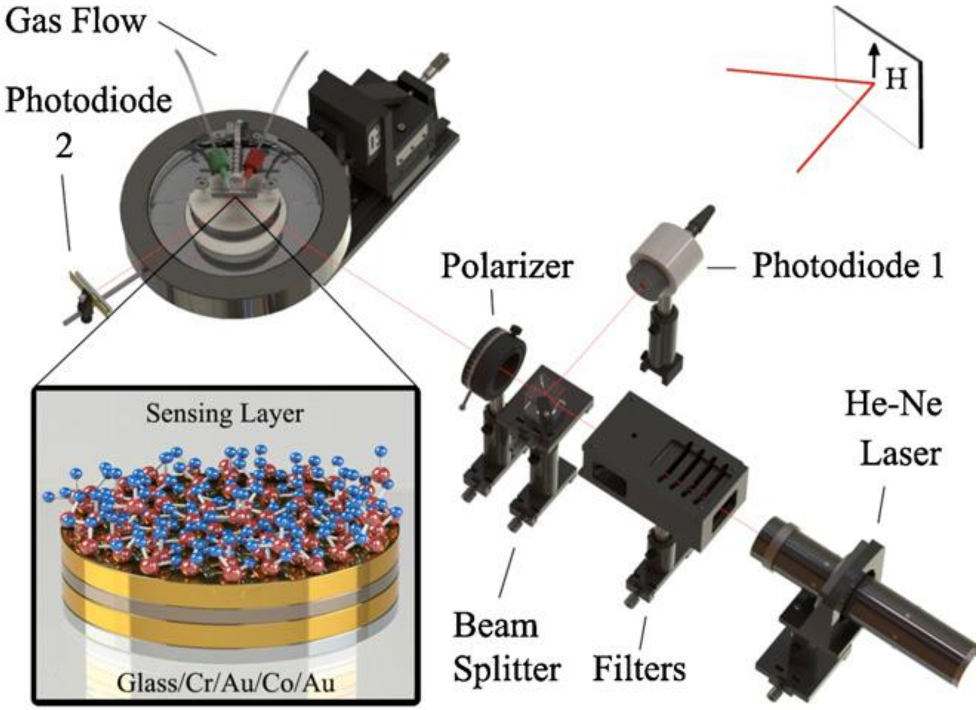
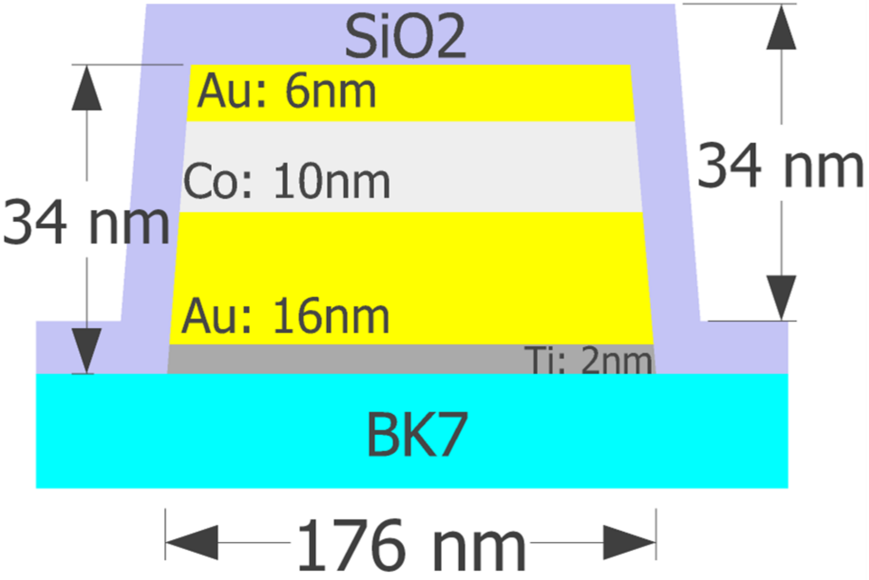
César Aurelio Herreño-Fierro and Edgar J. Patiño , PSSb, Volume 252, Issue 2 (2015) Pages 316–32

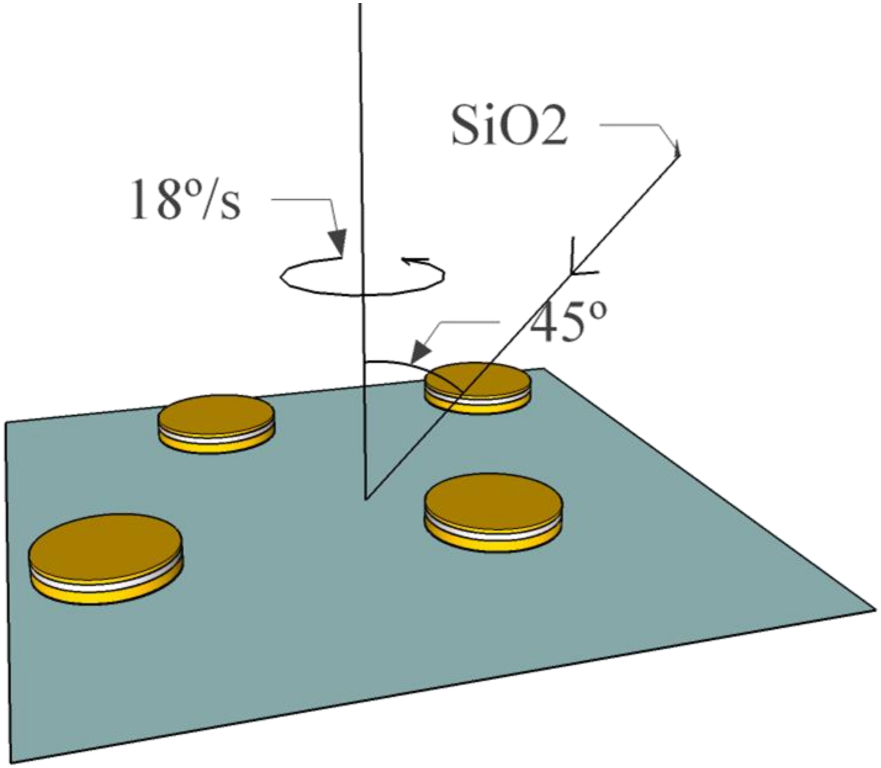
Magneto plasmons for sensing ?

- MO-SPR sensors



M.G. Manera et al. Sensors and Actuators B 182 (2013) 232– 238

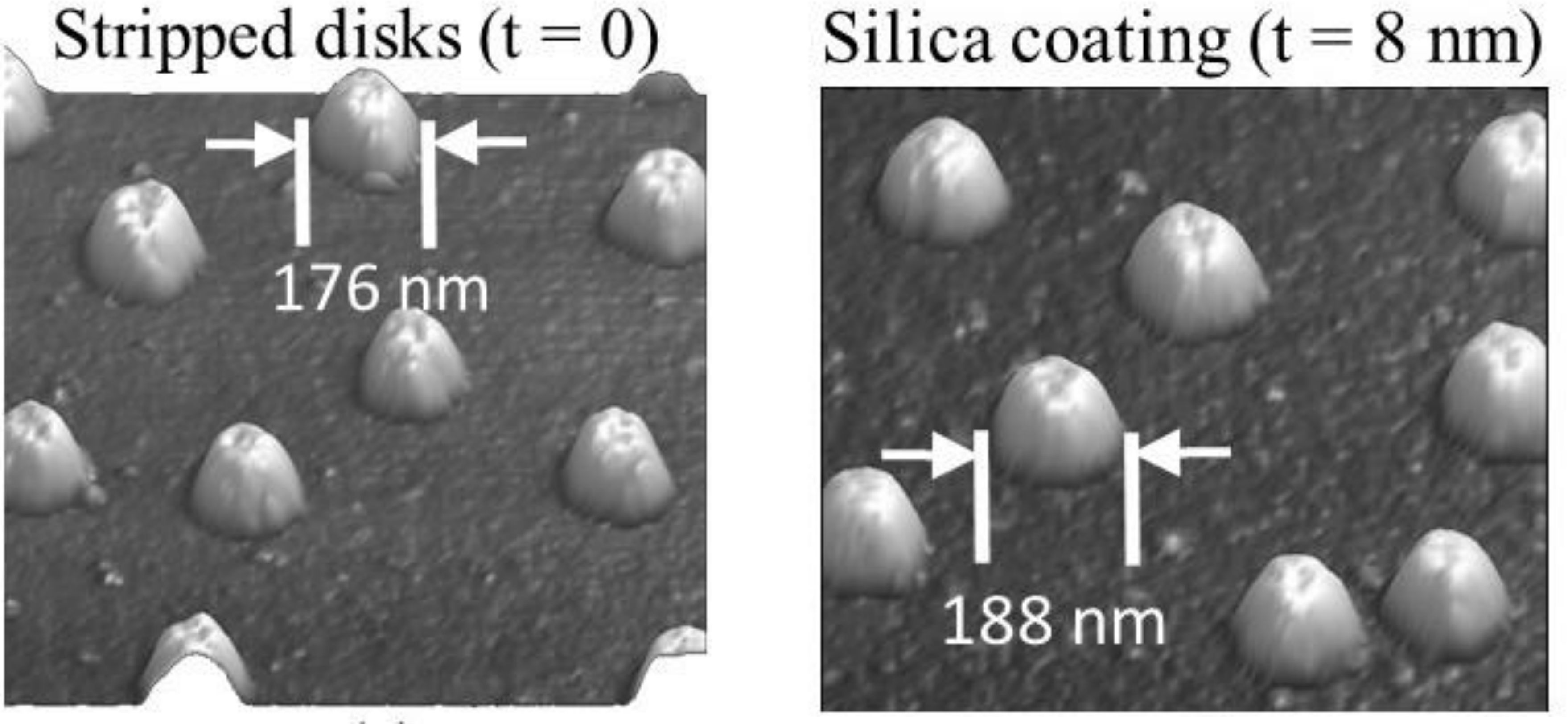




C. A. Herreño-Fierro and E. J. Patiño, “Maximization of surface-enhanced transversal magneto-optic Kerr effect in Au/Co/Au thin films”, PSSb, **252**, 2, 316–322 (2015)

Characterization:

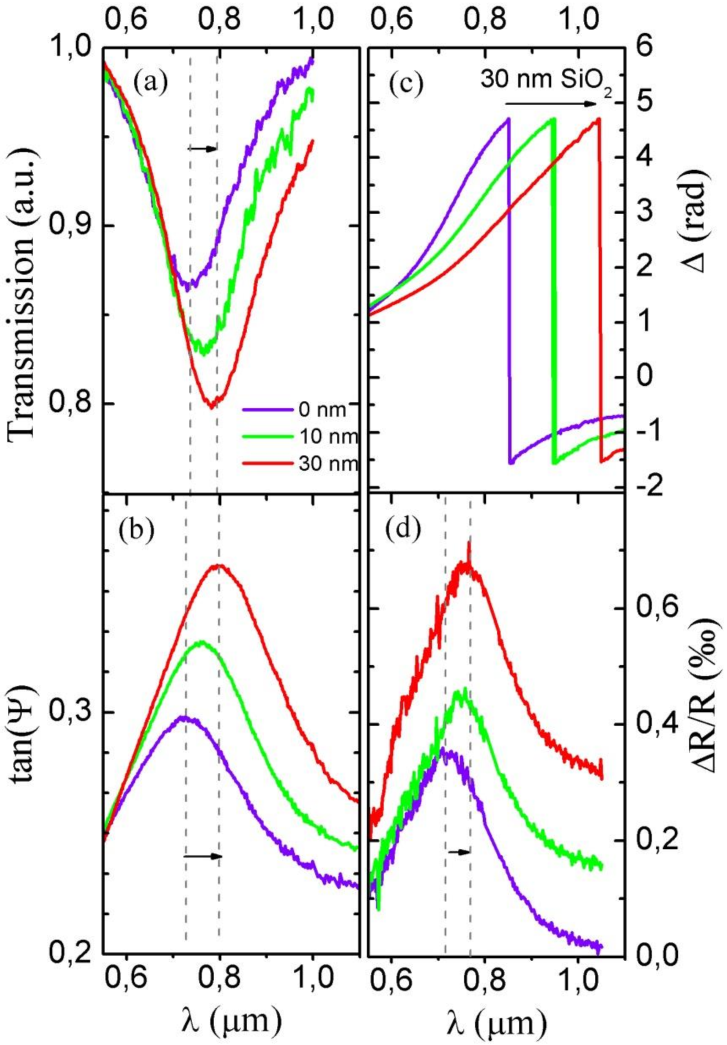
Morphology

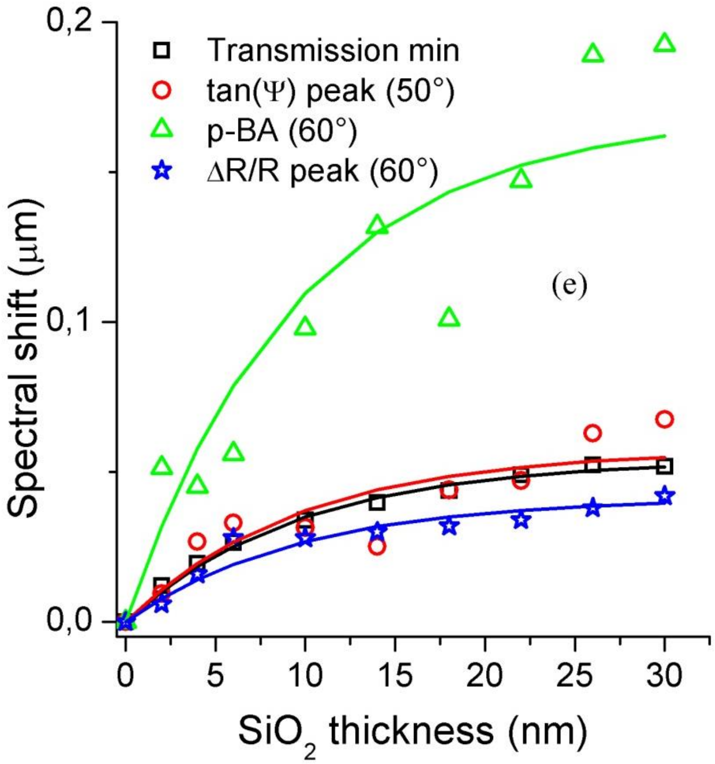

Stripped disks (t = 0)

Silica coating (t = 8 nm)

AFM images

What are the results?





C. Herreño, **E. J. Patiño**, A. Cebollada, G. Armelles G. ***Applied Physics Letters*** 108 (2), pp. 0211091-0211094. 2016

AIP | Applied Physics Letters

Conclusions

- It is posible to maximize the MOKE signal in structures M/F/M by manipulation of relative thicknesses of each layer.
- Nano disk of M/F/M structures show the largest sensitivity to SiO2 deposition.

Quantum tunneling: How long does it take ?

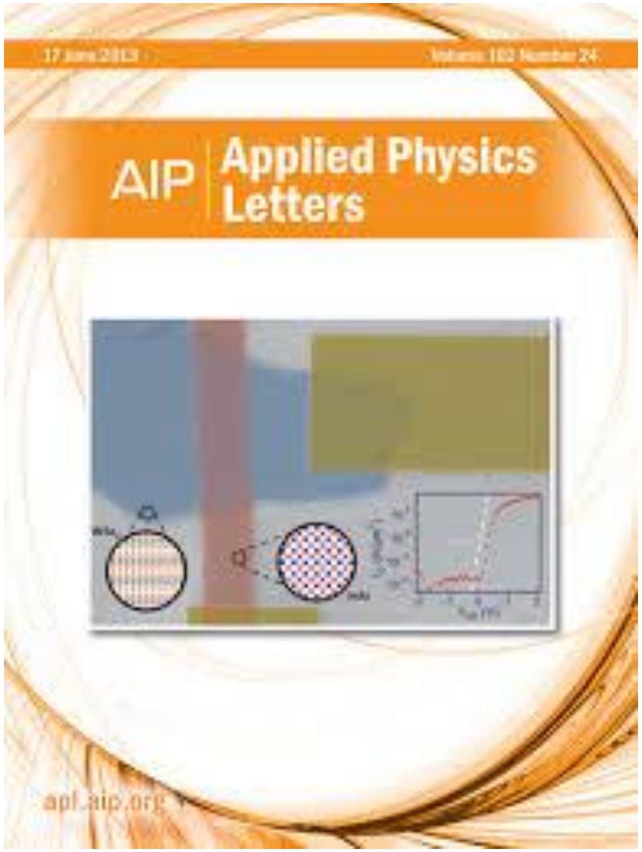
/www.wired.com/2010/12/wormhole-detection/

Edgar J. Patiño

Departamento de Física

Universidad de los Andes
Colombia

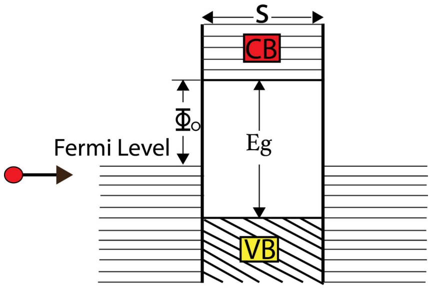
COLCIENCIAS
Ciencia, Tecnología e Innovación



E. J. Patiño and N. Kelkar “**Experimental determination of tunneling characteristics and dwell times from temperature dependence of Al/Al2O3/Al junctions**”
Applied Physics Letters 107 (25) 2015

Not possible without the help of:

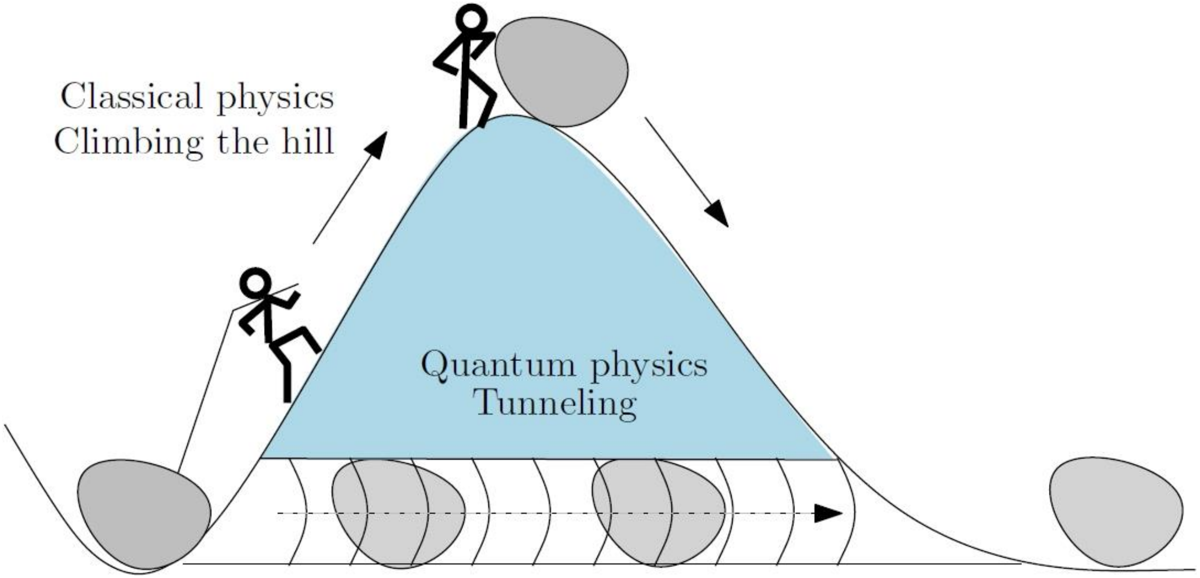
Neelima Kelkar



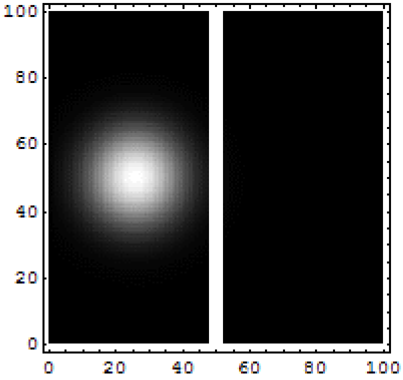
During this talk…..

- Introduction and Motivation-> Quantum Tunneling. Why tunneling is important in solid state physics? Some preliminary works…
- Experiments Description-> Additional information that can be extracted from tunneling experiments
- Tunneling Dwell time determination
- Conclusions

What is quatum tunneling



Source: tech for space

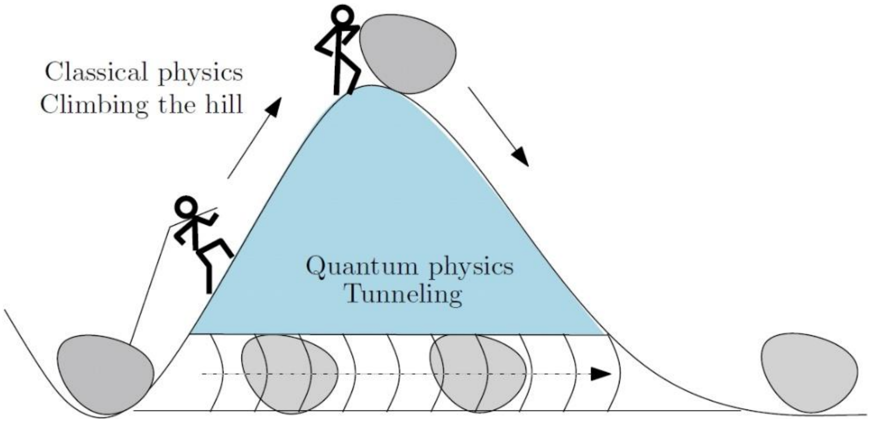


Electron wave packet propagation

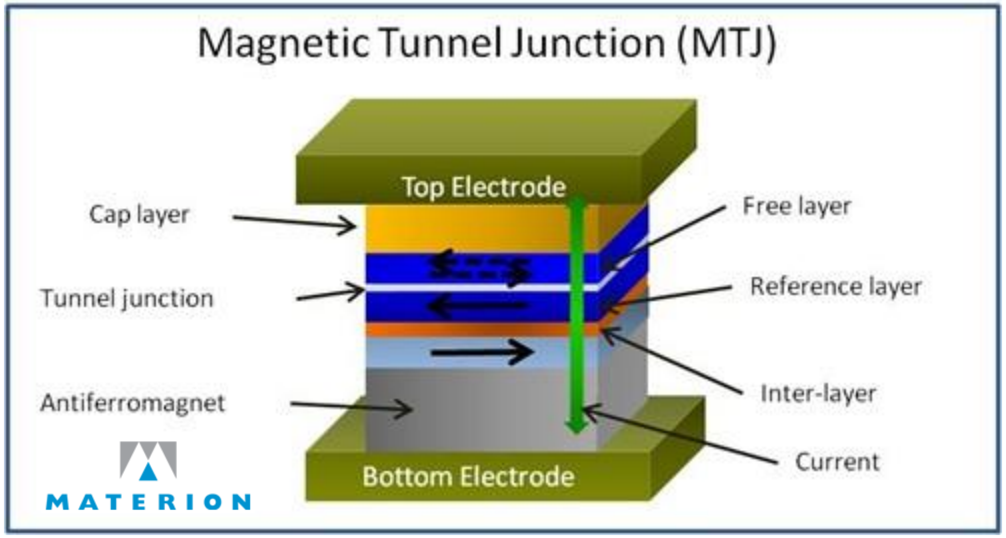
Source: Wikipedia

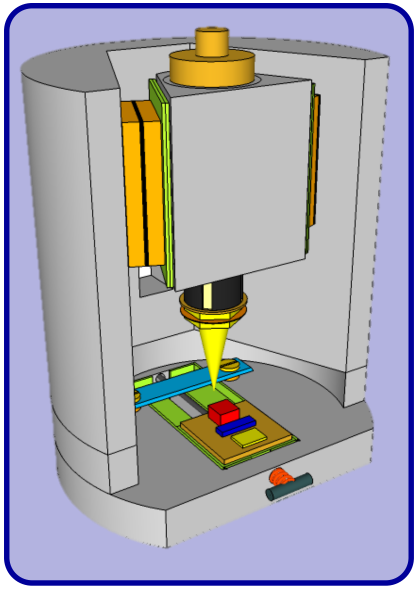
Other applications…..

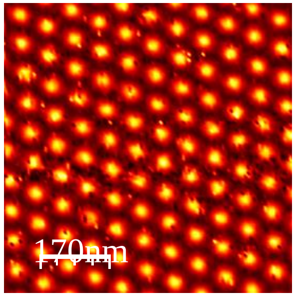
What is quantum tunneling?



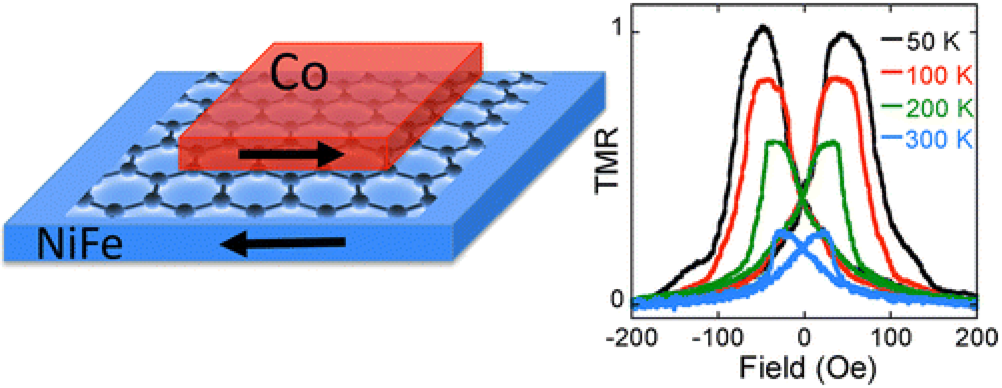
Source: tech for space





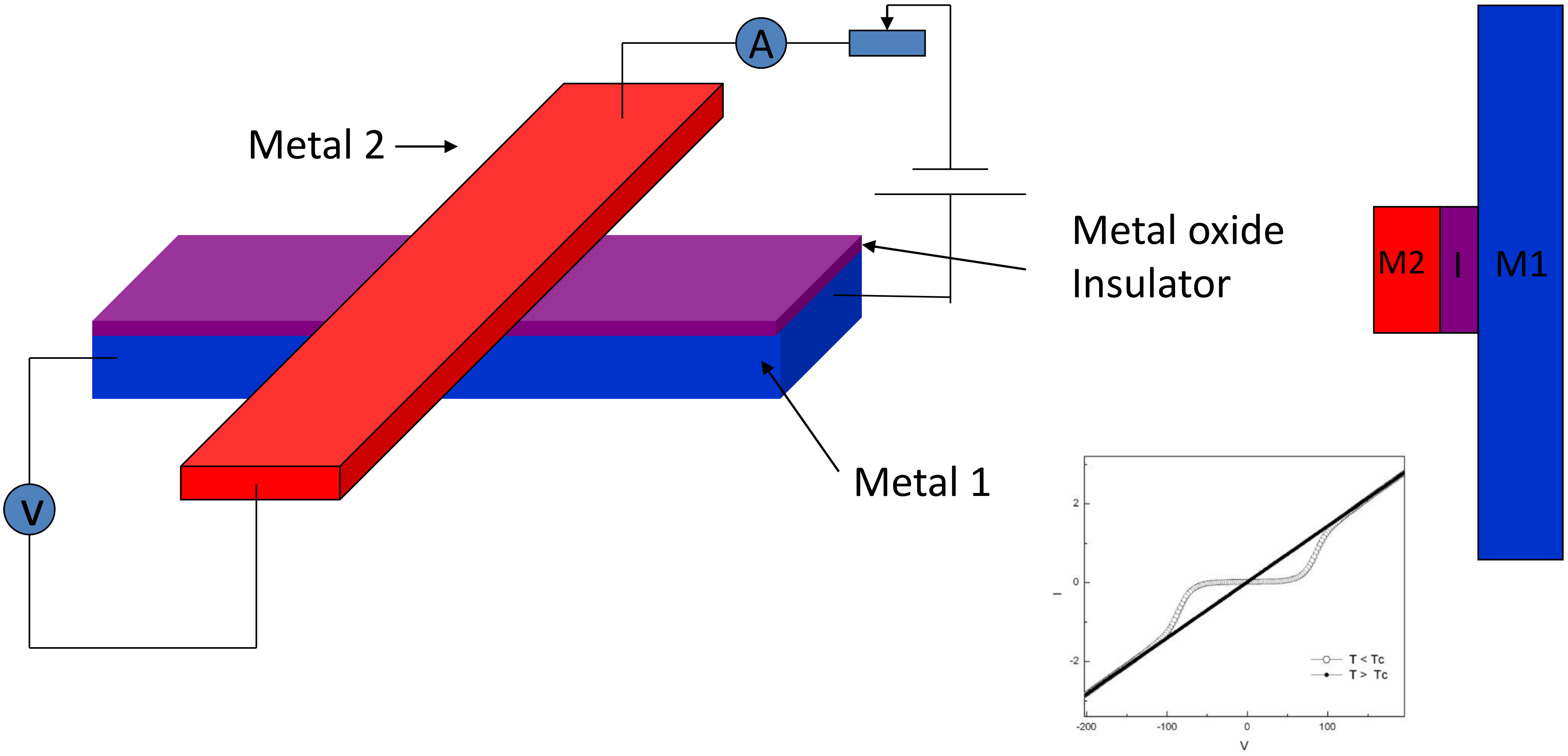


Vortex images
STM
shared
by Edwin Herrera



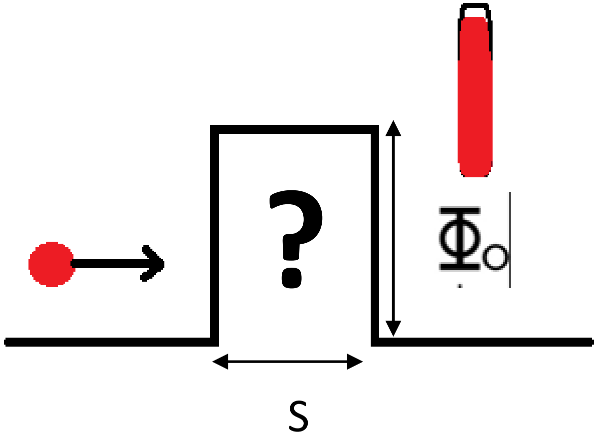
Graphene As a Tunnel Barrier: Graphene-Based Magnetic Tunnel JunctionsNano Lett., 2012, 12 (6), pp 3000–3004 (2012)

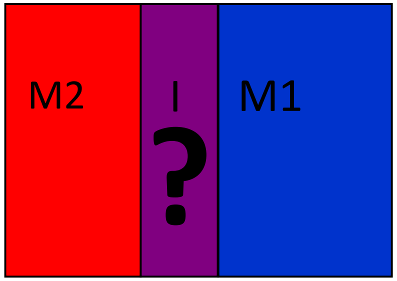
How to make a solid state tunnel junction ?



These structures can be fabricated utilizing mechanical masks or standard optical lithography techniques

What people knew before?





- **Barrier height** decreases with increasing temperature (up to 77 K)….?
- CONTROVERTIAL EXPLANATIONS
  A) Is Al_2O_3 barrier height temperature dependence?
  B) Is there a change in the space charge in dielectric ?
  C) Are there trap levels in the insulator?
- Two reports on **barrier width** temperature variation

-> NO EXPLANATION (electron effective mass, maybe??)

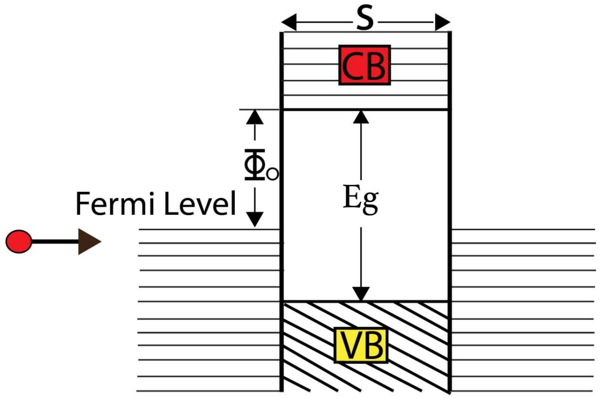
Difficult to produce continuous Al2O3 -> pinholes, hot spots and barrier shorts found!

.

[1] K. H. Gundlach and A. Wilkinson, Phys. Stat. Sol. (a) **2**, 295 (1970).
[2] O. L. Nelson and D. E. Anderson, J. Appl. Phys. 37, 77 (1966)
[3] J. Kadlec, Solid-State Electronics **17**, 469 (1974).
[4] V. D. Das and M. S. Jagadeesh, Phys. Stat. Sol. (a) **66**, 327 (1981).
[5] D. Meyerhofer and S. A. Ochs, J. Appl. Phys. **34**, 2535 (1963).

What do we need to know well in order to extract tunneling time ?

- Barrier width (s) and barrier height (ϕo)



New questions….

How to extract information from the barrier?

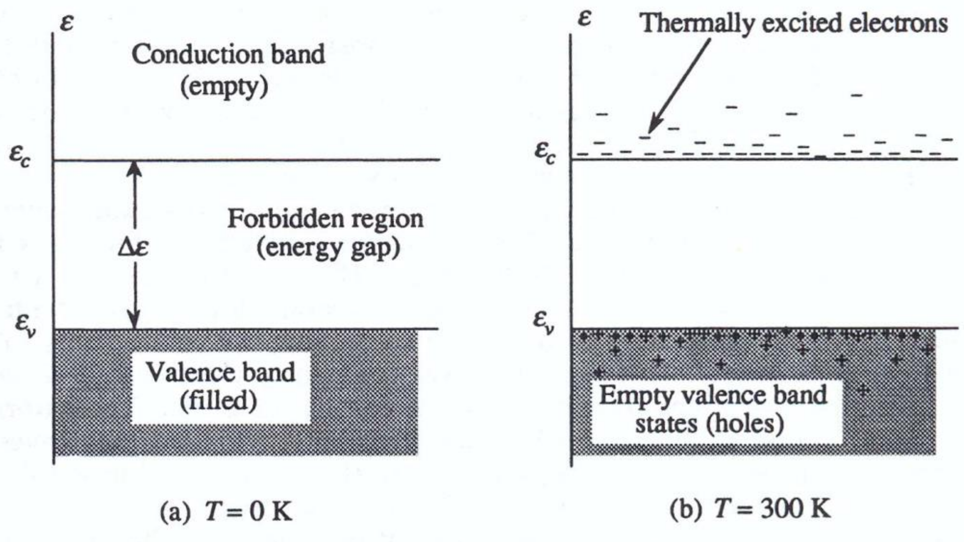
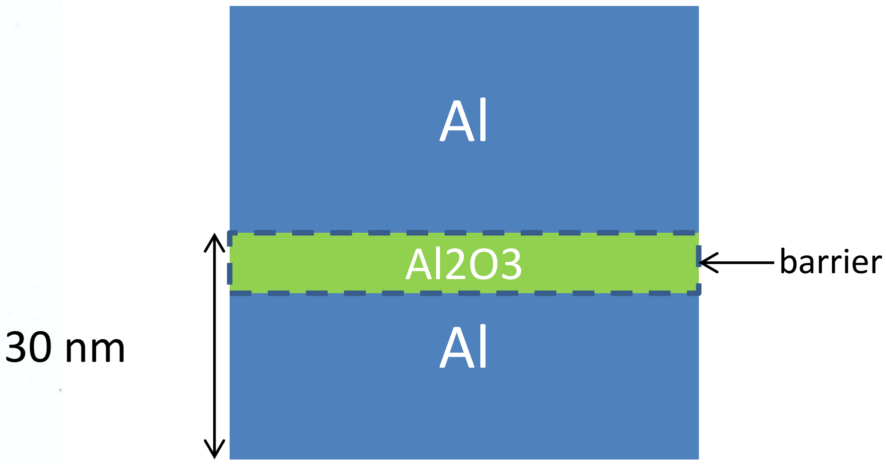
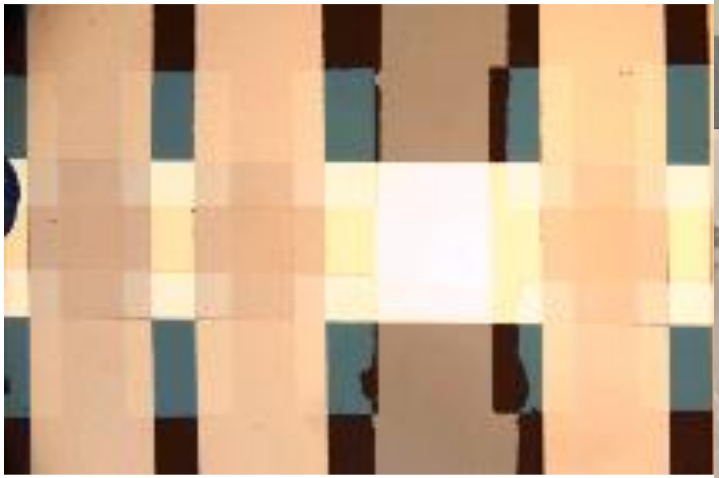
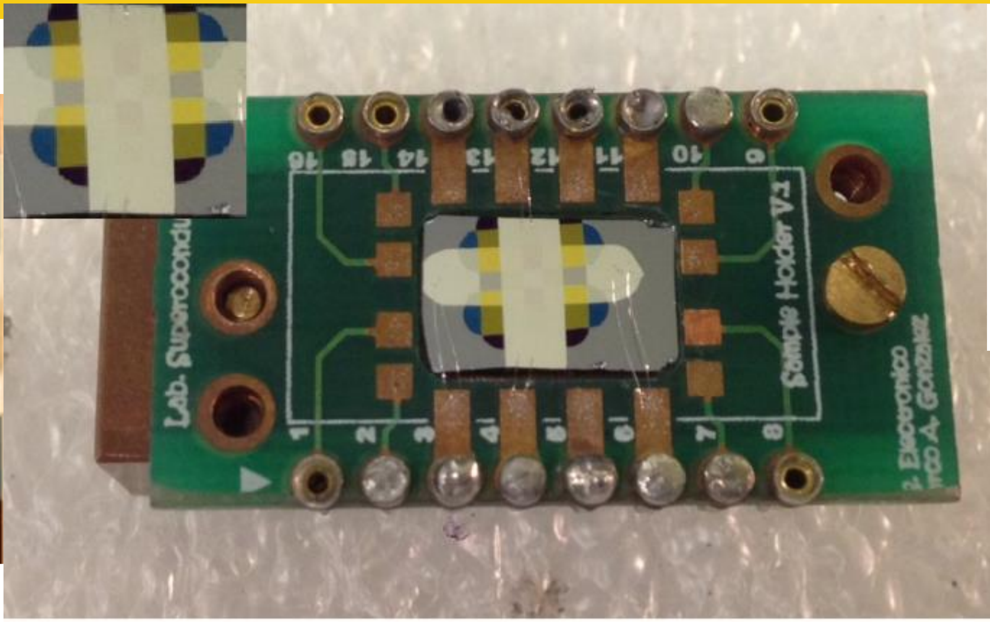


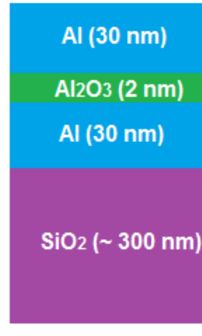
Figure 9.1 Conduction and valence bands of an intrinsic semiconductor (a) at temperature absolute zero, and (b) at room temperature, illustrating thermally excited electrons and empty valence band ststes associated with holes.

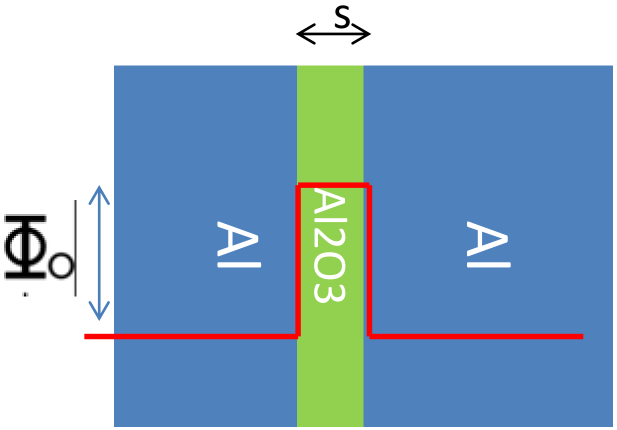


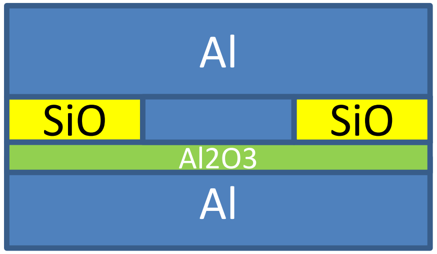
Tunnel junctions: Our experiment











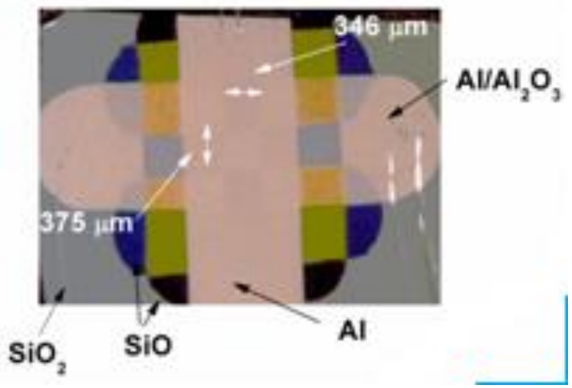
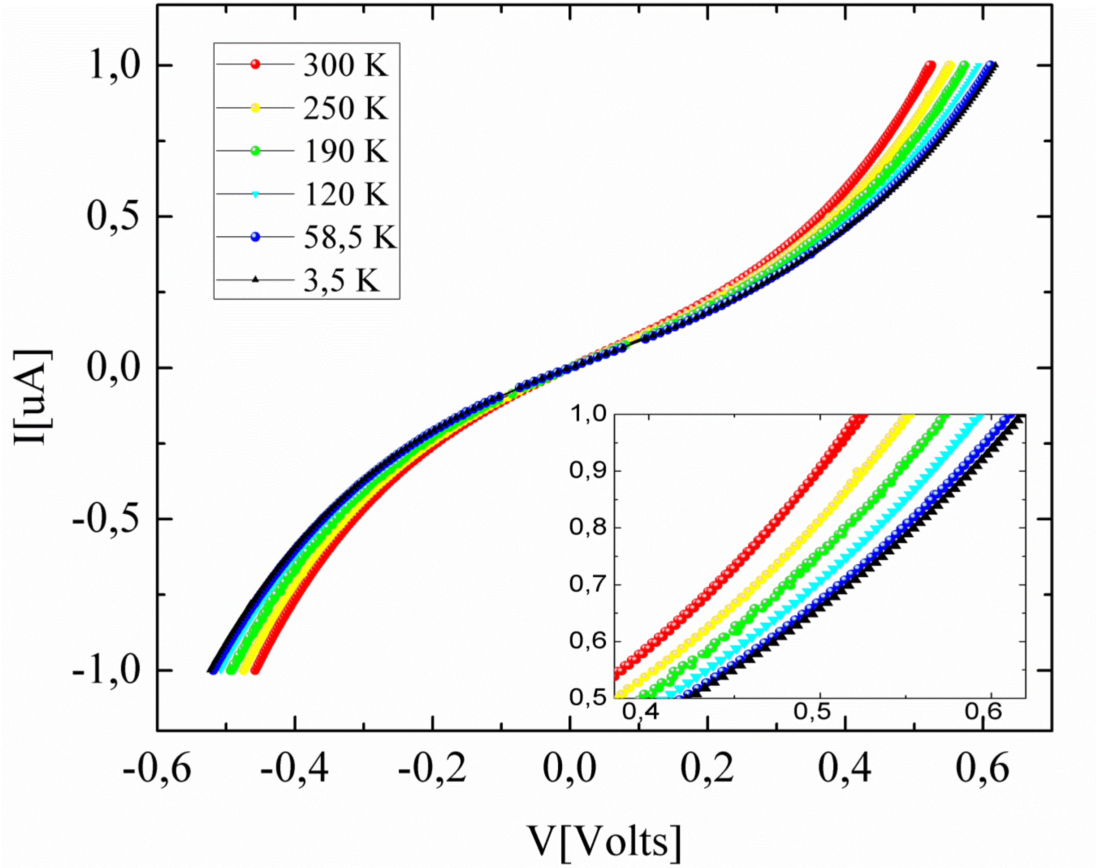
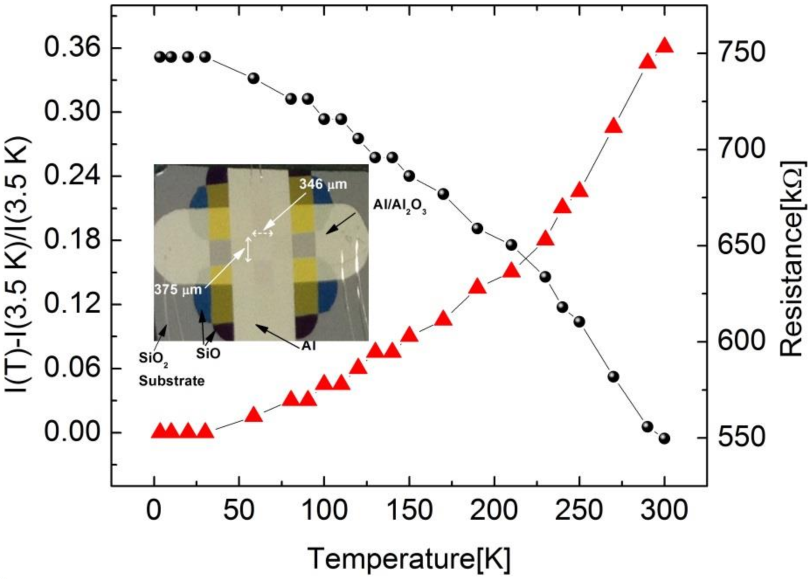


Figure 3: Photograph of planar junctions made using a mask evaporation technique in the system shown in figure. 1.

What are the results?



I-V characteristics of $Al/Al_2O_3/Al$ junctions at different temperatures; inset shows zoom in view upper voltages.

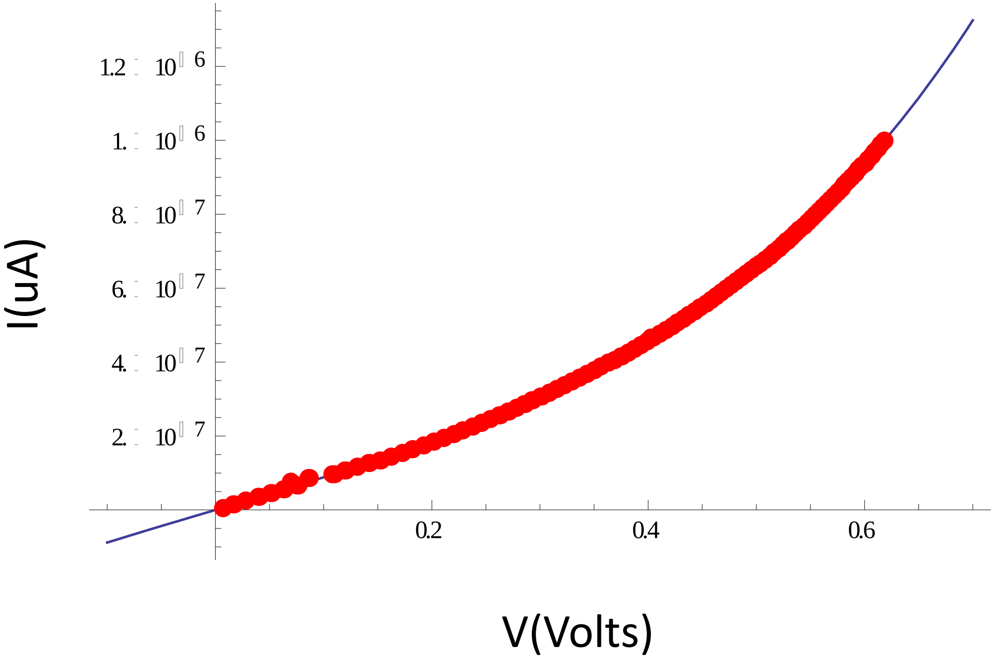


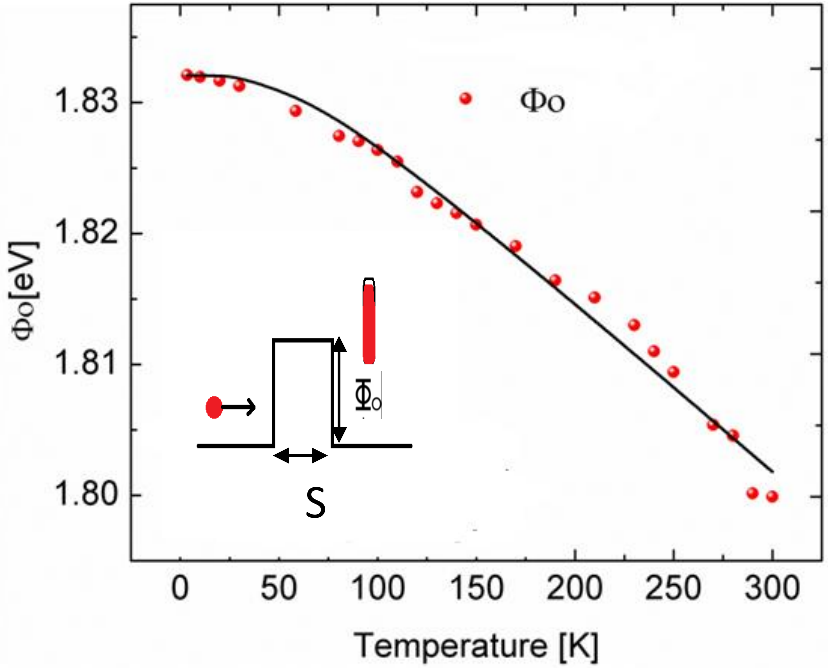
Junction Resistance (triangles) and Tunneling current variation (circles) vs temperature at a bias voltage of 0.5 V

Small temperature dependence!

How good is the theoretical fit with the experiment ?

$$J=\left(\frac{e}{2\pi h s^{2}}\right)\left\{\left(\varphi_0-\frac{eV}{2}\right)\exp\left[-\frac{4\pi s}{h}(2m)^{\frac{1}{2}}\left(\varphi_0-\frac{eV}{2}\right)^{\frac{1}{2}}\right]-\left(\varphi_0+\frac{eV}{2}\right)\exp\left[-\frac{4\pi s}{h}(2m)^{\frac{1}{2}}\left(\varphi_0+\frac{eV}{2}\right)^{\frac{1}{2}}\right]\right\}$$





	Estimate	Standard Error
φ_0	2.178	0.00249147
s	19.1074	0.0109113

A ≈ 375X346 (μm)^2

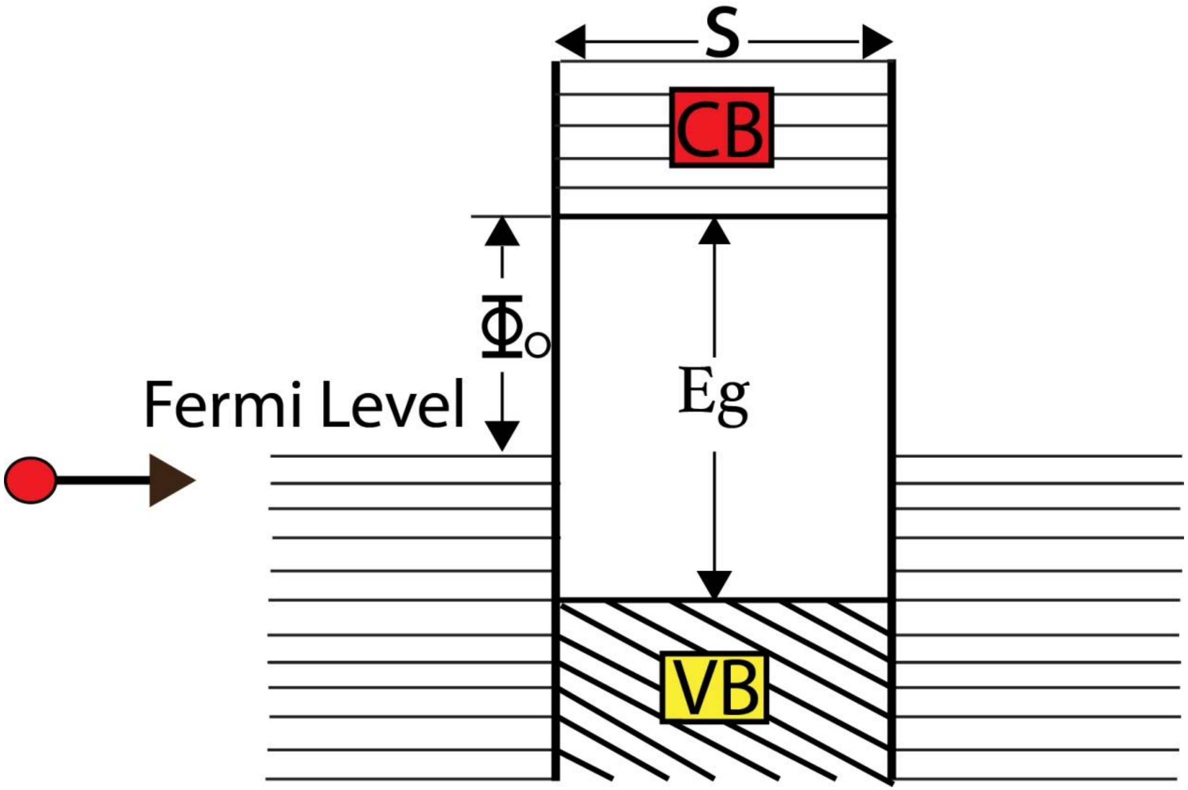
No pinholes of hot spots!

S ≈ 20.8 Å

Barrier width → Fixed at al Temperatures!

Simmons, J. G. (1963). "Generalized Formula for the Electri..." Journal of Applied Physics 34(6): 1793-1803.

Why is Φ_o changing with temperature ?



Assuming a linear relationship:

Eg(T)=γ ϕo(T)

$$\frac{Eg(300\ K)}{\Phi o(300K} = \frac{3.2\ eV\ *}{1.8\ eV}=1.7$$

Is Eg changing with temperature as well?

---

* I. Costina and R. Franchy, Appl. Phys. Lett. 78, 4139 (2001)

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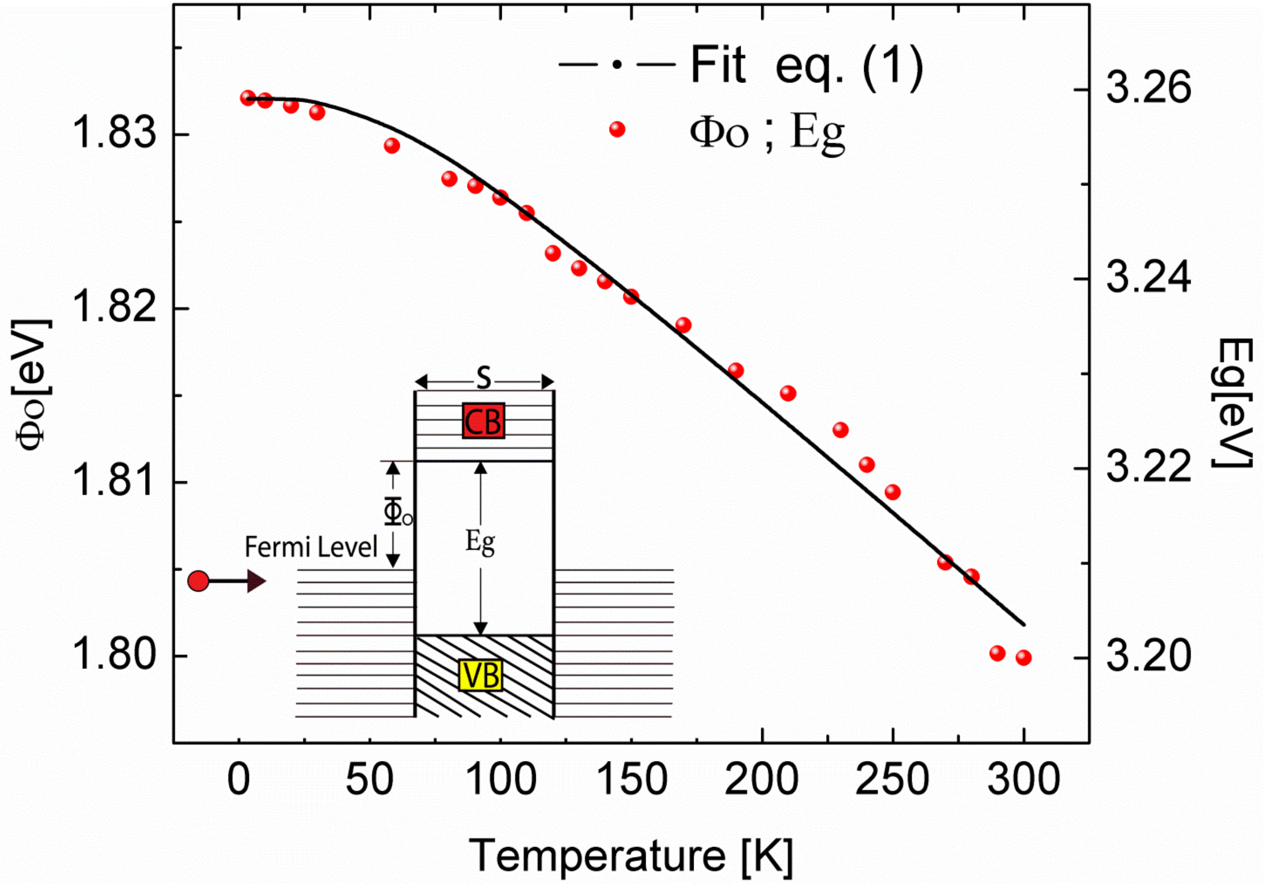
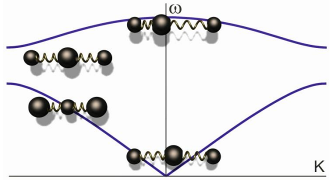
Eq. 1 $Eg(T) = Eg(0) - S\langle\hbar\omega\rangle[\coth(\langle\hbar w\rangle/2kT) - 1]$





$Eg(T) = \gamma\ \varphi o(T)$

↓

Eq. 1

↓

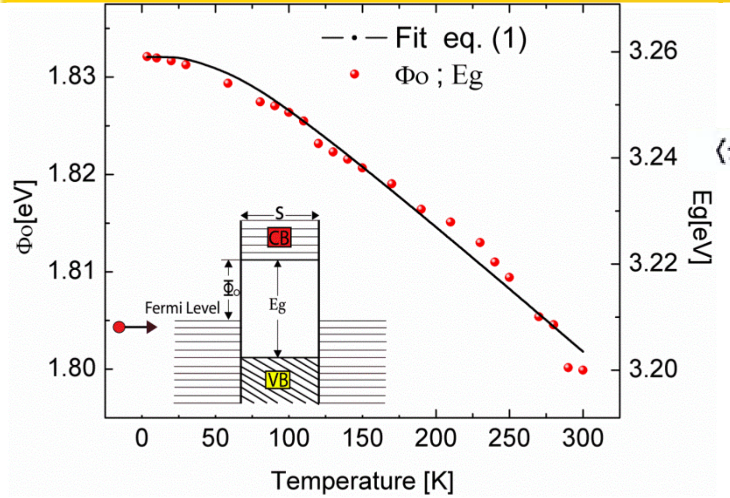
	Estimate	Standard Error
Ego	3.24348	0.00072269
S	1.16311	0.0613627
$\langle\hbar w\rangle$	0.0170526	0.00235379

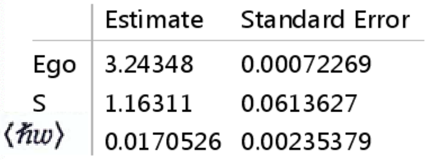
↓

Avg[ω] = 2.05x 10^{13} sec^{-1}

Eq.1:O’Donnell, K. P. and X. Chen (1991). "Temperature dependence of semiconductor band gaps." Applied Physics Letters 58(25): 2924-2926.

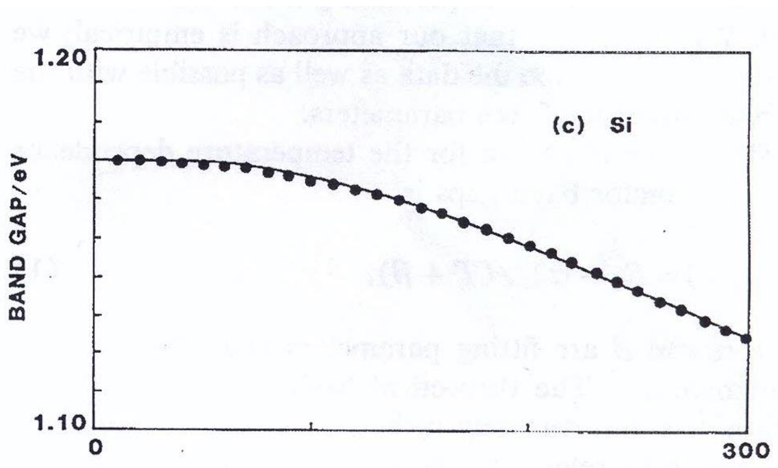
Comparing with other semiconductors: O’Donnel

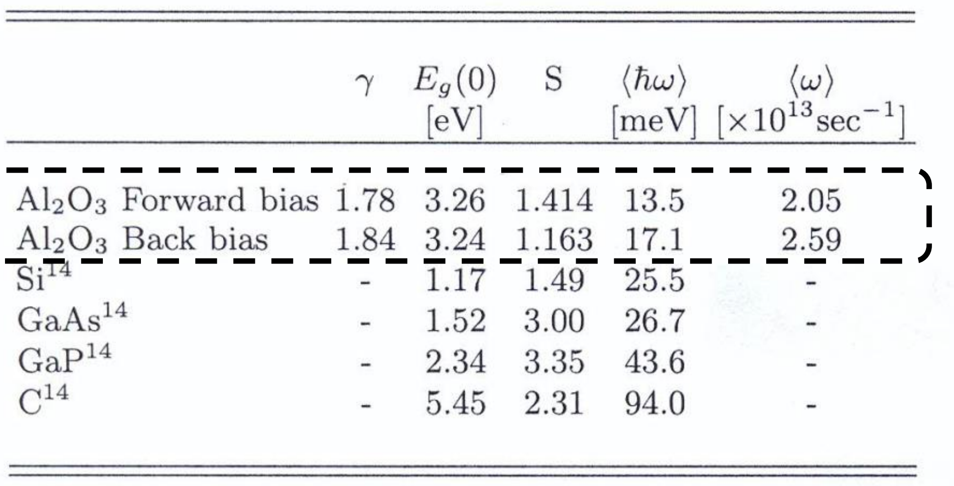




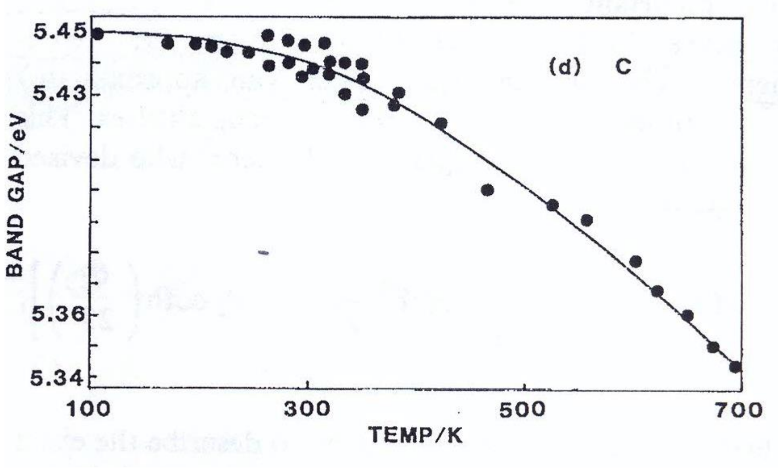
	Estimate	Standard Error
Ego	3.24348	0.00072269
S	1.16311	0.0613627
$\langle \hbar w \rangle$	0.0170526	0.00235379

↑ Average phonon energy





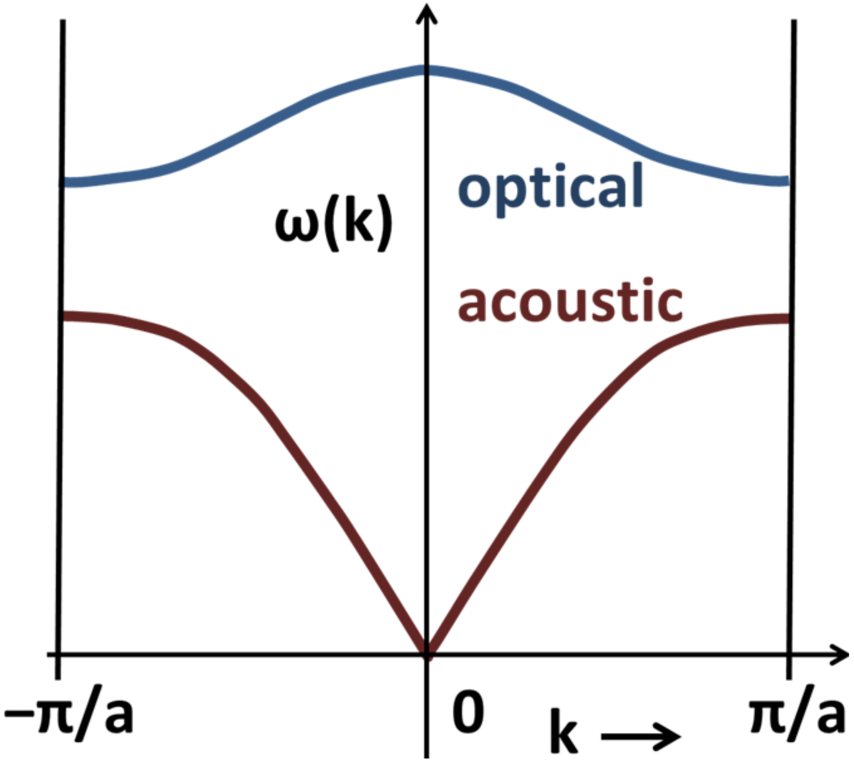
	γ	$E_g(0)$ [eV]	S	$\langle \hbar\omega \rangle$ [meV]	$\langle \omega \rangle$ $[\times 10^{13} \mathrm{sec}^{-1}]$
Al_2O_3 Forward bias	1.78	3.26	1.414	13.5	2.05
Al_2O_3 Back bias	1.84	3.24	1.163	17.1	2.59
Si[14]	-	1.17	1.49	25.5	-
GaAs[14]	-	1.52	3.00	26.7	-
GaP[14]	-	2.34	3.35	43.6	-
C[14]	-	5.45	2.31	94.0	-

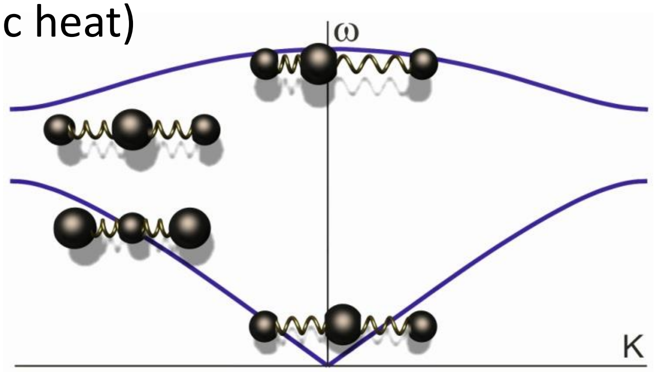


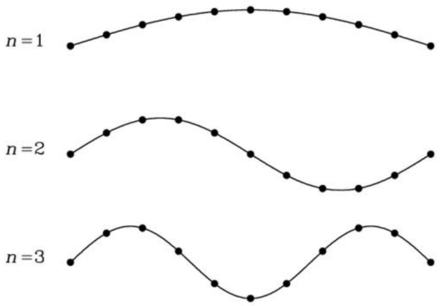
[14]O’Donnell, K. P. and X. Chen (1991). "Temperature dependence of semiconductor band gaps." Applied Physics Letters 58(25): 2924-2926.

Lets compare with other experiments….

Phonons- quantized atomic lattice vibrations (eg. Specific heat)







Avg[ω] = 2.05x 10^{13} sec^{-1}

K =2π/λ

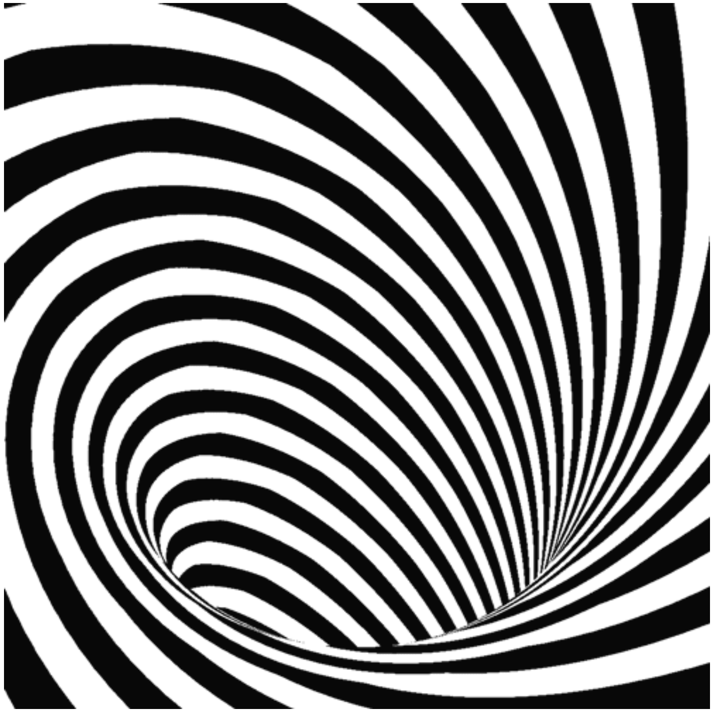
sound velocity v_{Al2O3} = 6.7 x 10^3 m/s. Considering a value of k=Pi/2a at the middle of the first Brillouin zone, from the expression ω = v_{Al2O3} k;

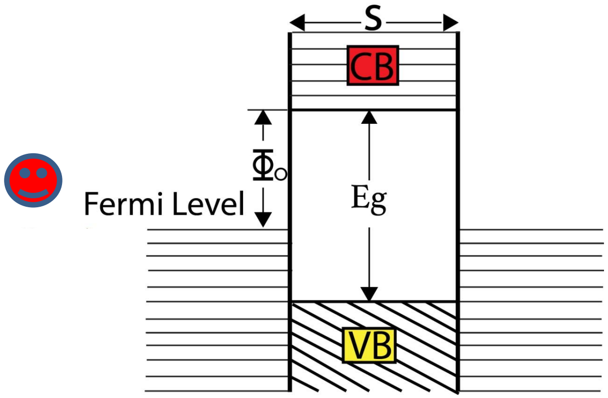
a value of phonon frequency **ω = 2.24 x 10^{13} sec^{-1} is obtained !**

We confirm..

Given that phonon frequencies are correct we confirm…..

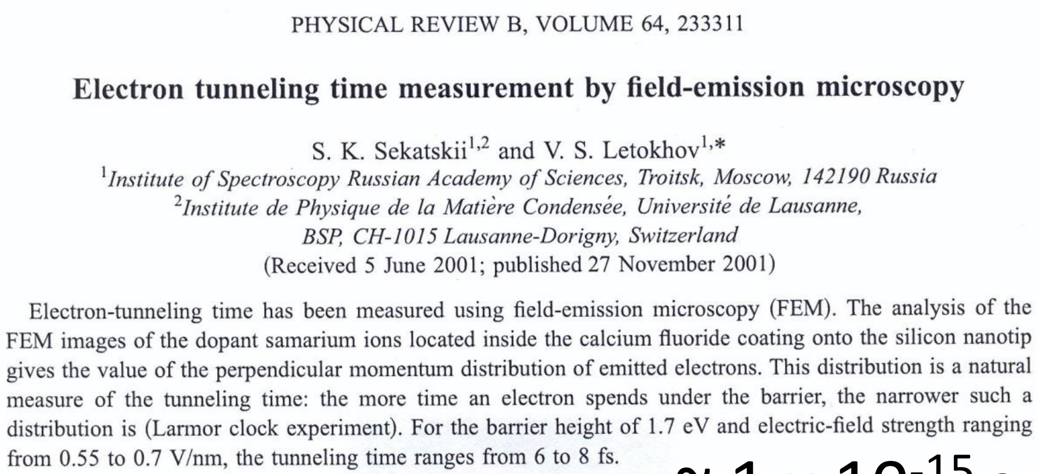
Barrier width “s” and height “ϕo ” are indeed correct!





http://www.vdomck.org/2009/11/ssh-all-time.html

How hard is to meassure tunneling times?



PHYSICAL REVIEW B, VOLUME 64, 233311

Electron tunneling time measurement by field-emission microscopy

S. K. Sekatskii[1,2] and V. S. Letokhov[1,*]
[1]*Institute of Spectroscopy Russian Academy of Sciences, Troitsk, Moscow, 142190 Russia*
[2]*Institute de Physique de la Matière Condensée, Université de Lausanne,*
BSP, CH-1015 Lausanne-Dorigny, Switzerland
(Received 5 June 2001; published 27 November 2001)

Electron-tunneling time has been measured using field-emission microscopy (FEM). The analysis of the FEM images of the dopant samarium ions located inside the calcium fluoride coating onto the silicon nanotip gives the value of the perpendicular momentum distribution of emitted electrons. This distribution is a natural measure of the tunneling time: the more time an electron spends under the barrier, the narrower such a distribution is (Larmor clock experiment). For the barrier height of 1.7 eV and electric-field strength ranging from 0.55 to 0.7 V/nm, the tunneling time ranges from 6 to 8 fs.

~ 1×10^{-15} s

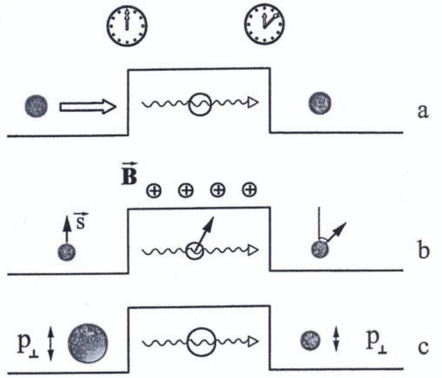


FIG. 1. The idea of the Larmor clock tunneling time measurement. One should invent a clock that starts to measure at the beginning of the barrier crossing and finishes at the end (a). Particle spin vector s rotation in the perpendicular magnetic field **B**, superimposed in the barrier region (b), or transversal momentum suppression (c) can be used as such a clock.

LETTER

doi:10.1038/nature11025

Resolving the time when an electron exits a tunnelling barrier

Dror Shafir[1]*, Hadas Soifer[1]*, Barry D. Bruner[1], Michal Dagan[1], Yann Mairesse[2], Serguei Patchkovskii[3], Misha Yu. Ivanov[4,5], Olga Smirnova[5] & Nirit Dudovich[1]

The tunnelling of a particle through a barrier is one of the most fundamental and ubiquitous quantum processes. When induced by an intense laser field, electron tunnelling from atoms and molecules initiates a broad range of phenomena such as the generation of attosecond pulses[1], laser-induced electron diffraction[2,3] and holography[2,4]. These processes evolve on the attosecond timescale (1 attosecond = 1 as =10^{-18} seconds) and are **well suited to the investigation of a general issue much debated since the early days of quantum mechanics**[5–7]—the link between the tunnelling of an electron through a barrier and its dynamics outside the barrier.

Previous experiments have measured tunnelling rates with attosecond time resolution[8] and tunnelling delay times[9]. Here we study **laser-induced tunnelling** by using a weak probe field to steer the tunnelled electron in the lateral direction and then monitor the effect on the **attosecond light bursts emitted** when the liberated electron re-encounters the parent ion[10]. We show that this approach allows us to measure the time at which the electron exits from the tunnelling barrier. We demonstrate the high sensitivity of the measurement by detecting **subtle delays in ionization times from two orbitals of a carbon dioxide molecule**. Measurement of the tunnelling process is essential for all attosecond experiments where strong-field ionization initiates ultrafast dynamics[10]. Our approach provides a general tool for time-

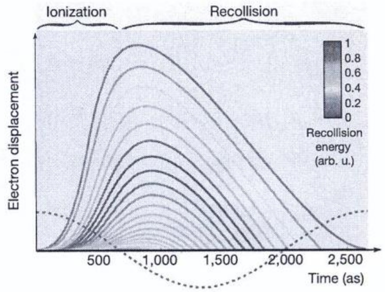
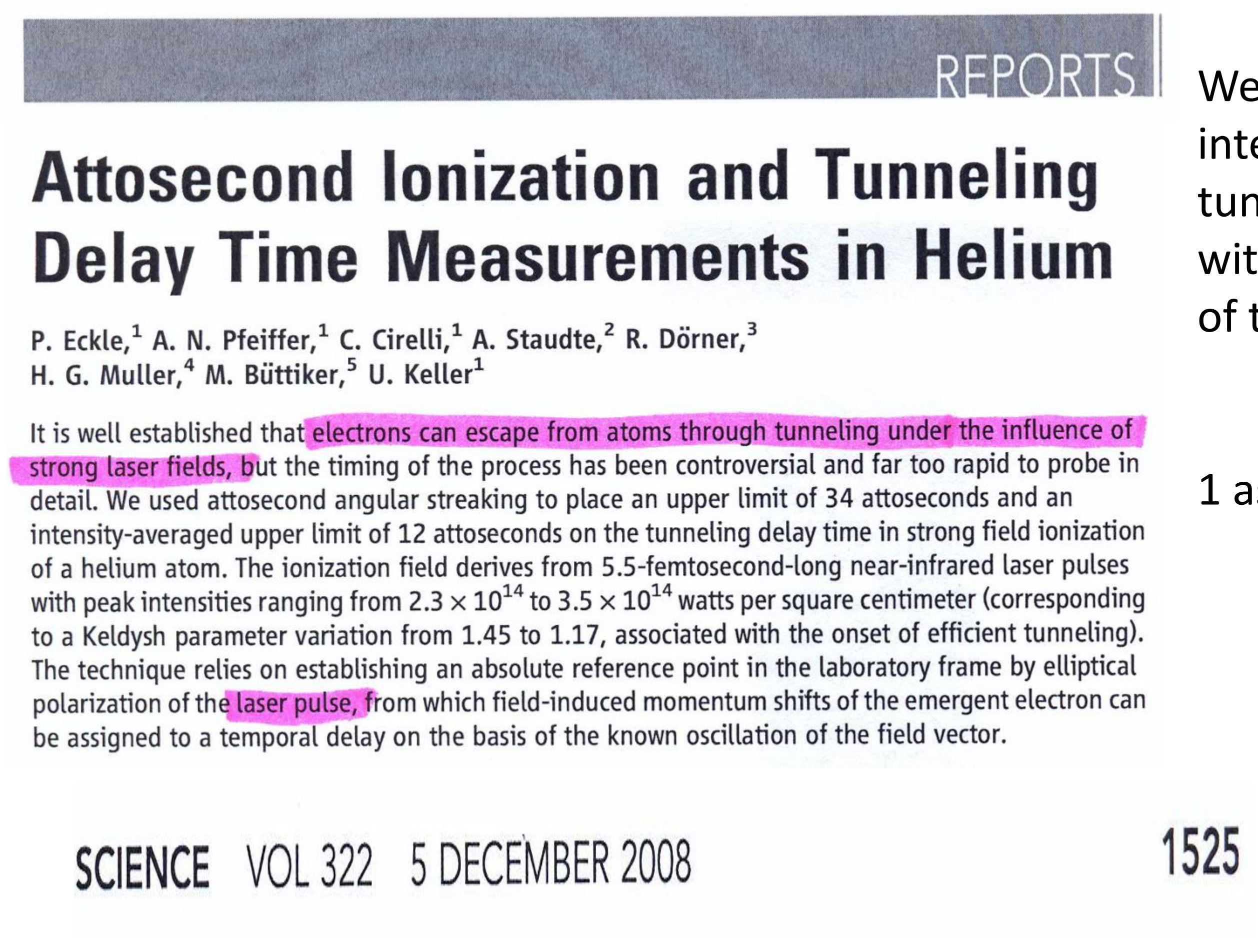


Figure 1 | Electron trajectories contributing to the recollision proces coloured lines represent the spatio-temporal description of various traje each colour encodes a recolliding energy, increasing from red to blue. Th dashed line shows the electric field along the cycle. arb. u., arbitrary un



Attosecond Ionization and Tunneling Delay Time Measurements in Helium

P. Eckle,[1] A. N. Pfeiffer,[1] C. Cirelli,[1] A. Staudte,[2] R. Dörner,[3]
H. G. Muller,[4] M. Büttiker,[5] U. Keller[1]

It is well established that electrons can escape from atoms through tunneling under the influence of strong laser fields, but the timing of the process has been controversial and far too rapid to probe in detail. We used attosecond angular streaking to place an upper limit of 34 attoseconds and an intensity-averaged upper limit of 12 attoseconds on the tunneling delay time in strong field ionization of a helium atom. The ionization field derives from 5.5-femtosecond-long near-infrared laser pulses with peak intensities ranging from 2.3×10^{14} to 3.5×10^{14} watts per square centimeter (corresponding to a Keldysh parameter variation from 1.45 to 1.17, associated with the onset of efficient tunneling). The technique relies on establishing an absolute reference point in the laboratory frame by elliptical polarization of the laser pulse, from which field-induced momentum shifts of the emergent electron can be assigned to a temporal delay on the basis of the known oscillation of the field vector.

We measured a weighted intensity-averaged tunneling delay time of 6.0 as with a standard deviation of the weighted mean of 5.6 as

1 as ~ 1 x 10^{-18} s

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How long does an electron take to tunnel through a Al2O3 barrier?

Dwell time (tiempo de habitabilidad)

$$\tau_D(E) = \frac{\int_{x_1}^{x_2} |\Psi(x)|^2 \, dx}{j}, \qquad \textit{Eq. 1}$$

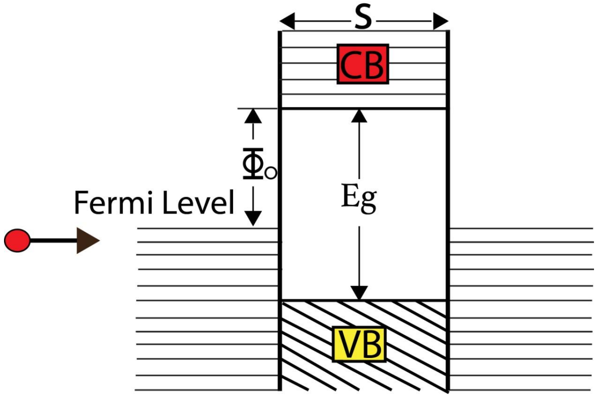
x_1, x_2, are the classical turning points

momentum

⇩

$$j = \hbar k/\mu$$ ⇦ *reduced mass*

$$k = \sqrt{2mE}/\hbar$$

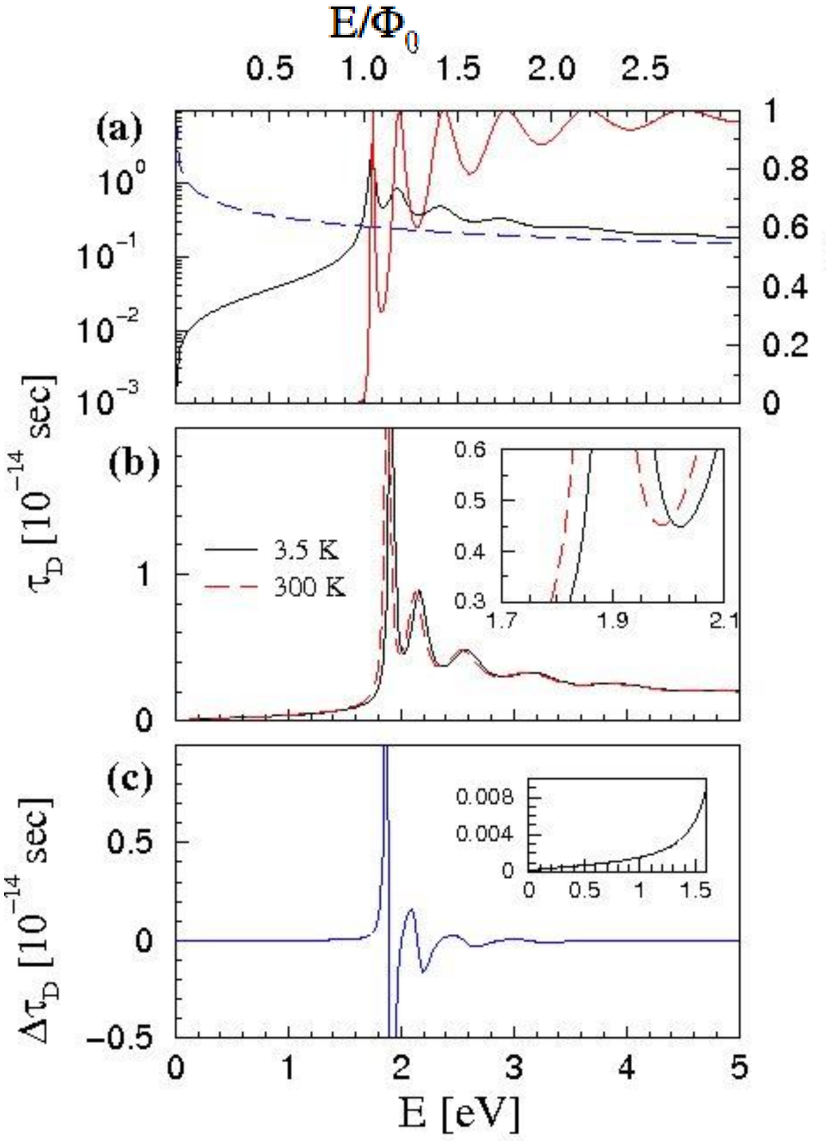


Finding the wave function and solving eq. 1 for a rectangular barrier of fixed height and width for $E < \Phi_0$

Smith F. (1960). “Lifetime Matrix in Collision Theory " Physical Review 118(1): 349

Buttiker M. (1983). “Larmor precession and the traversal time for tunneling” Physical Review B 27(10) 6178

Finding the wave function and solving eq. 1 for a rectangular barrier :



Average dwell times spent by tunneling electrons within the potential barrier

(a) As a function of the energy divided by the barrier height. The trans-mission coefficient (red line- right scale)

(b) As a function of the energy for two different temperatures.

(c) Difference between the dwell time curves at 3.5 and 300 K. Pronounced mostly 300K 3.5K in the resonance regions $\Delta\tau_D = \tau_D$ (3.5K)$-\tau_D$(300K))

The trans-mission coefficient (red line with scale on righ side in (a)).

τ_D = 3.6 x 10^{-16} sec at mid barrier energies !

H. G. Winful, Phys. Rep. 436, 1 (2006); N. G. Kelkar, Phys. Rev. Lett. 99, 210403 (2007); M. Büttiker and R. Landauer, Phys. Rev. Lett. 49, 1739 (1982).

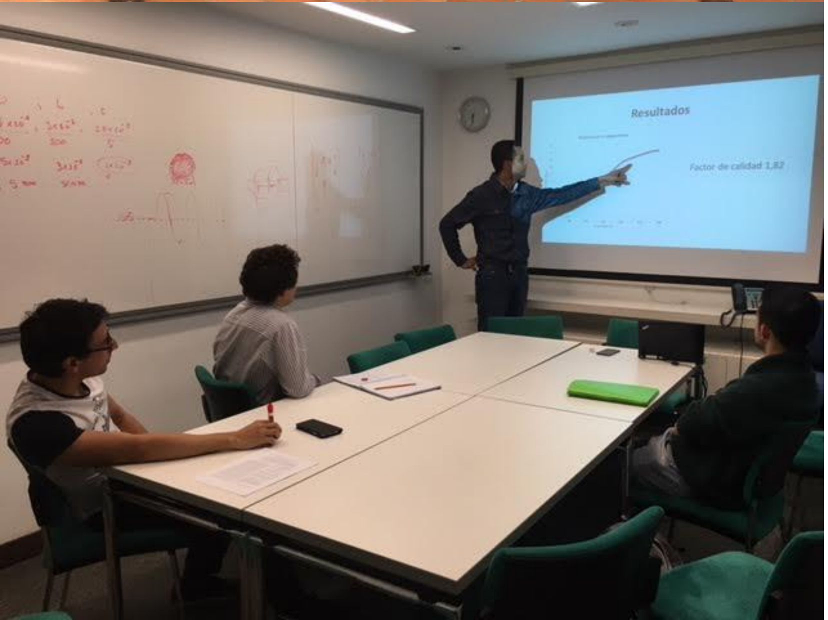
Conclusions

- Tunneling experiments demonstrate a **clear temperature dependence of the barrier height**
- The barrier height temperature dependence is directly linked to energy gap of the semiconductor BUT barrier width **S ≈ 20.8 Å** does not change.
- The phonon average frequency extracted **$\omega = 2.24 \times 10^{13}\ \mathrm{sec}^{-1}$** is very close to the one obtained from speed of sound experiments, proving this as an accurate technique .
- Tunneling time determined to be **3.6×10^{-16} sec** at mid-barrier energies
- Tunneling experiments in **other** thin semiconducting materials should provide useful information on energy gap and phonon spectrum

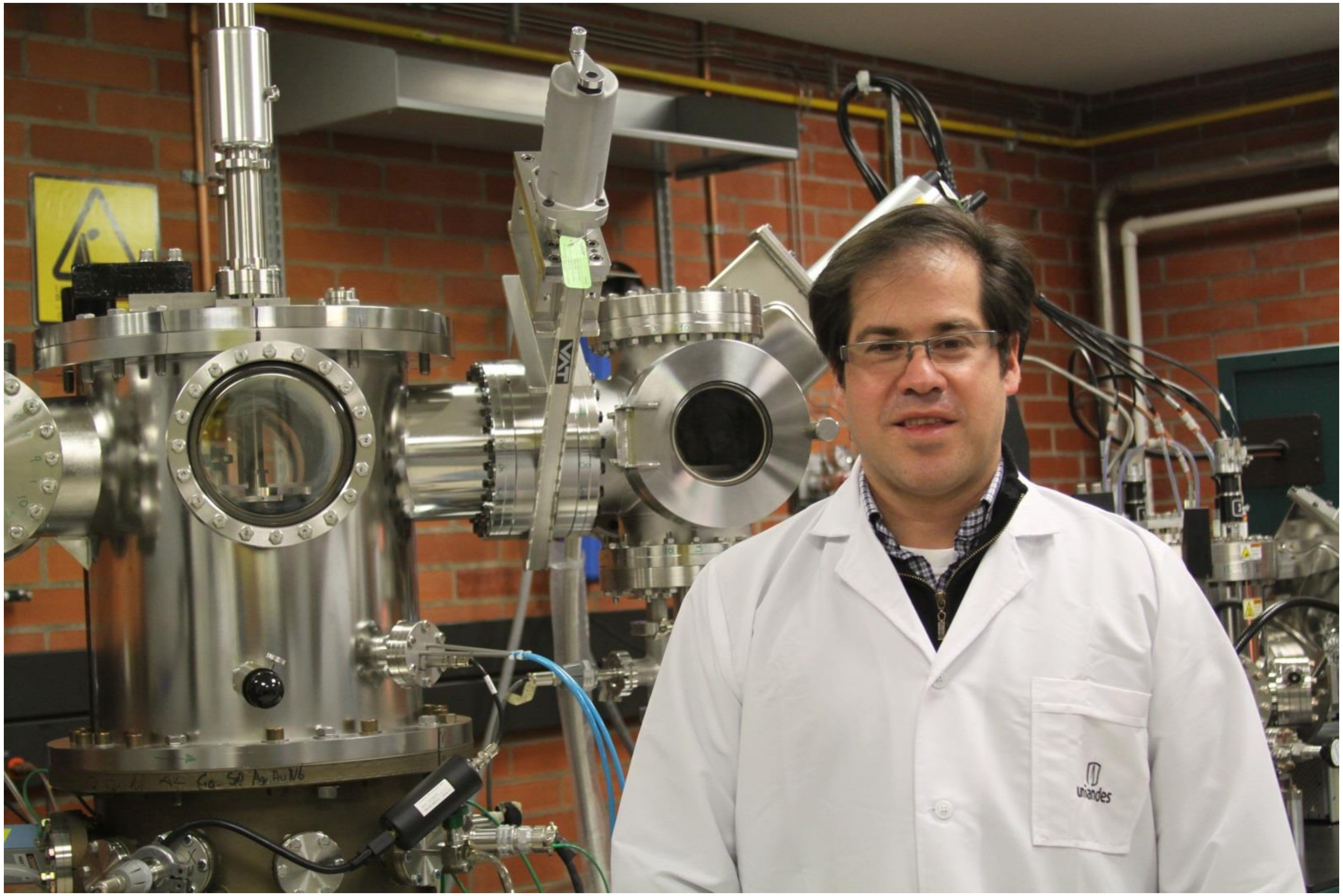
AIP | Applied Physics Letters

E. J. Patiño and N. Kelkar “**Experimental determination of tunneling characteristics and dwell times from temperature dep. of Al/Al2O3/Al junctions**” Applied Physics Letters 107 (25) 2015

Research group



Gracias!



Email: epatino@uniandes.edu.co