Tunneling in $Al/Al_2O_3/Al$ junctions and its direct link with energy gap and tunneling time across the barrier

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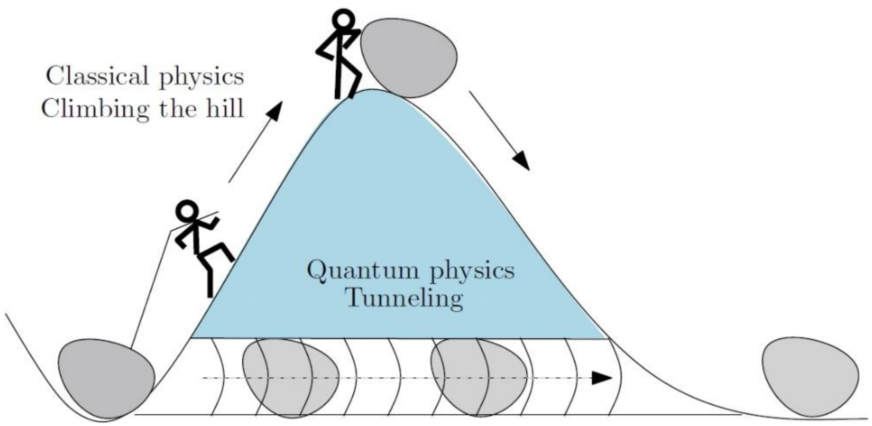
COLCIENCIAS
Ciencia, Tecnología e Innovación

During this talk.....

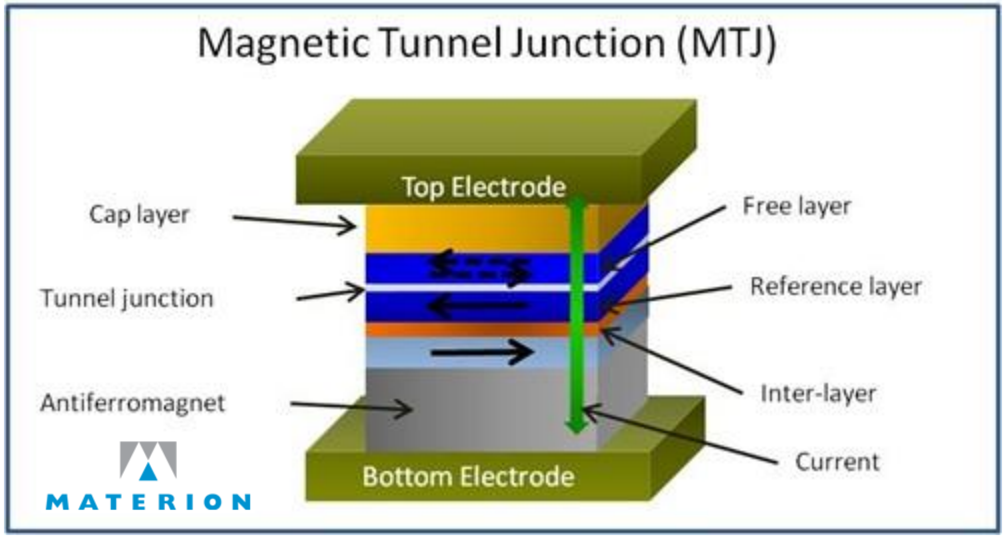
- Introduction and Motivation-> Quantum Tunneling. Why tunneling is important in solid state physics? Some preliminary works…
- Experiments Description-> Additional information that can be extracted from tunneling experiments
- Tunneling Dwell time determination
- Conclusions

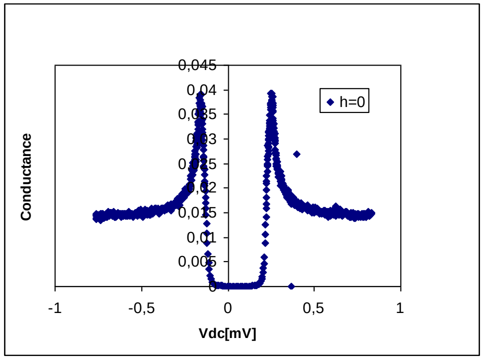
Other applications…..

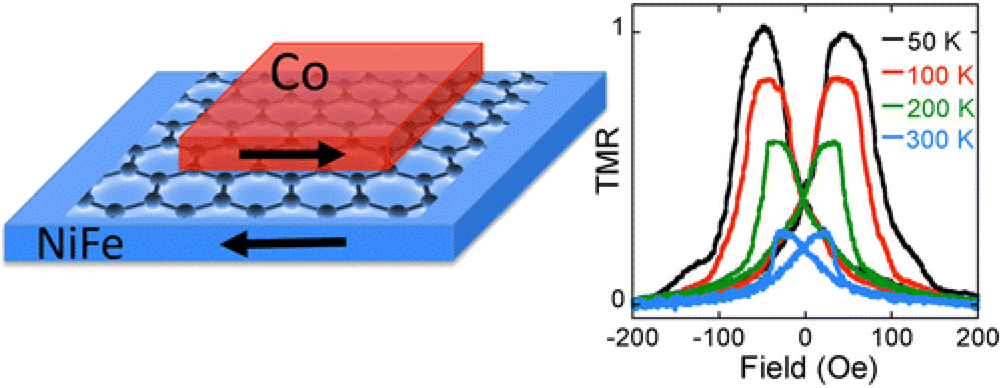
What is quantum tunneling?



Source: tech for space







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

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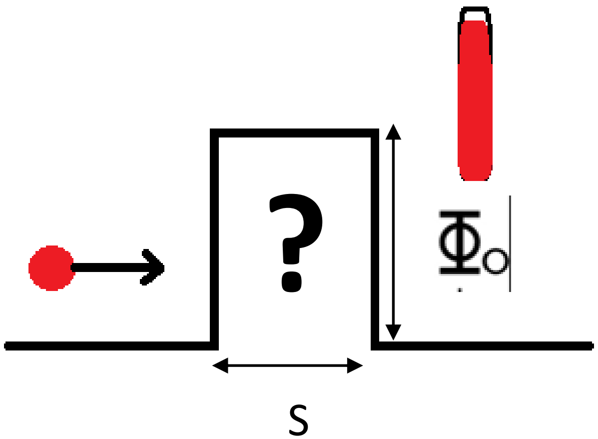
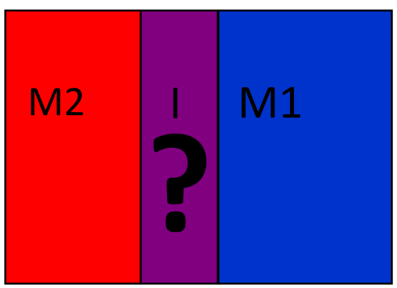
What people knew before?





- **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

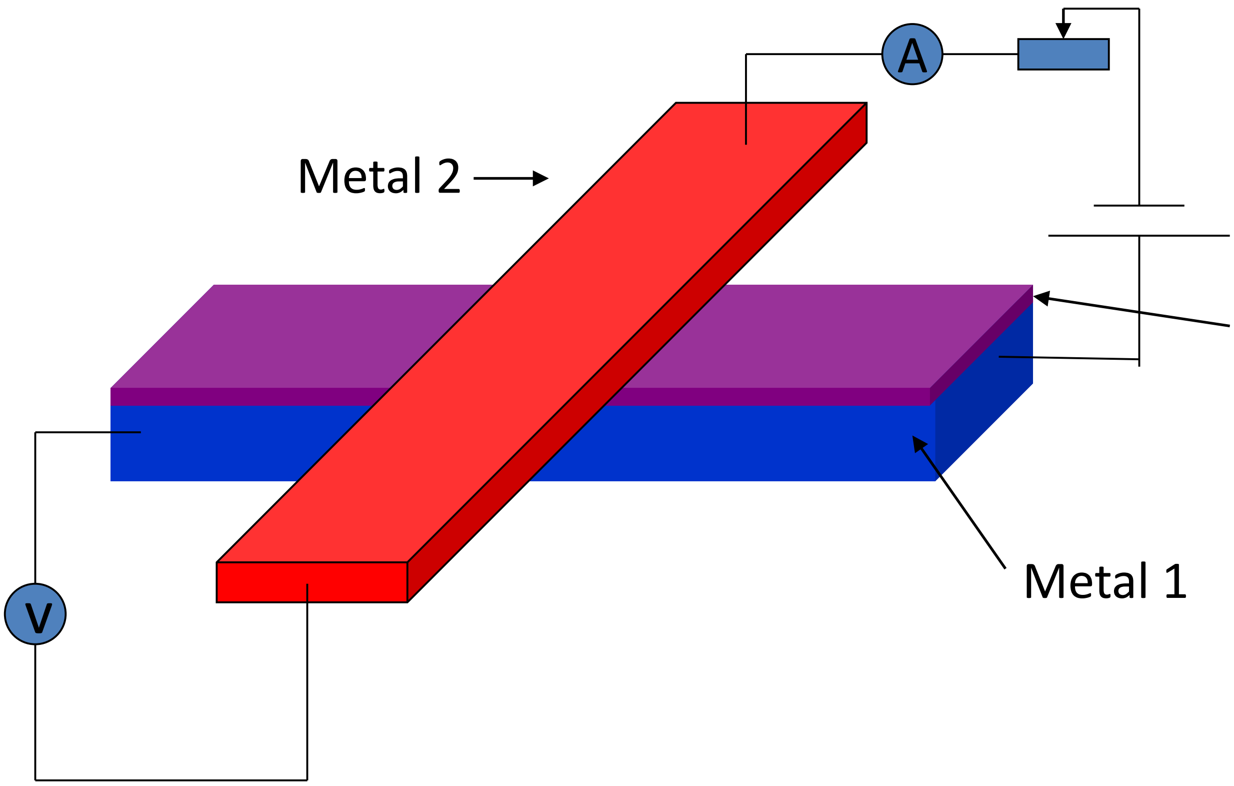
-> NO EXPLANATION (electron effective mass, maybe??)

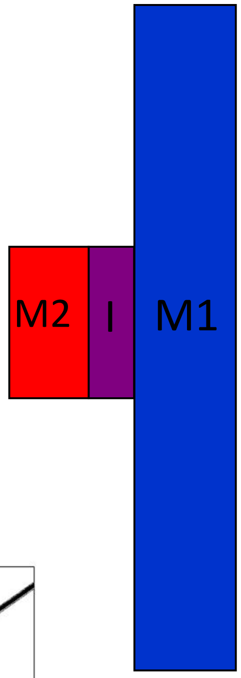
Difficult to produce continuous Al2O3 -> pinholes, hot spots and barrier shorts found!

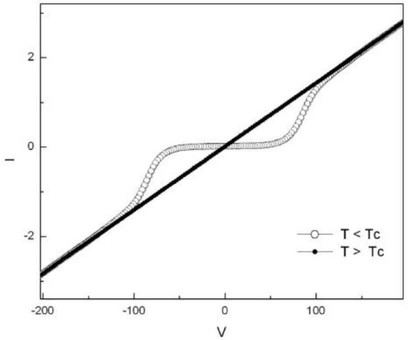
.

[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).

How to make a solid state tunnel junction ?

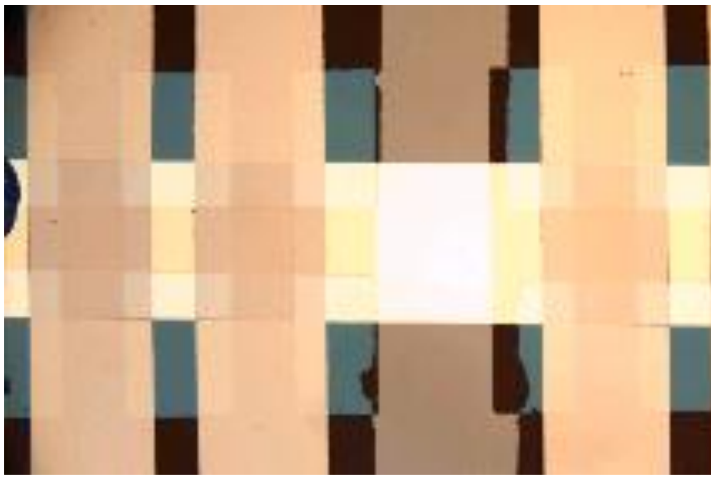


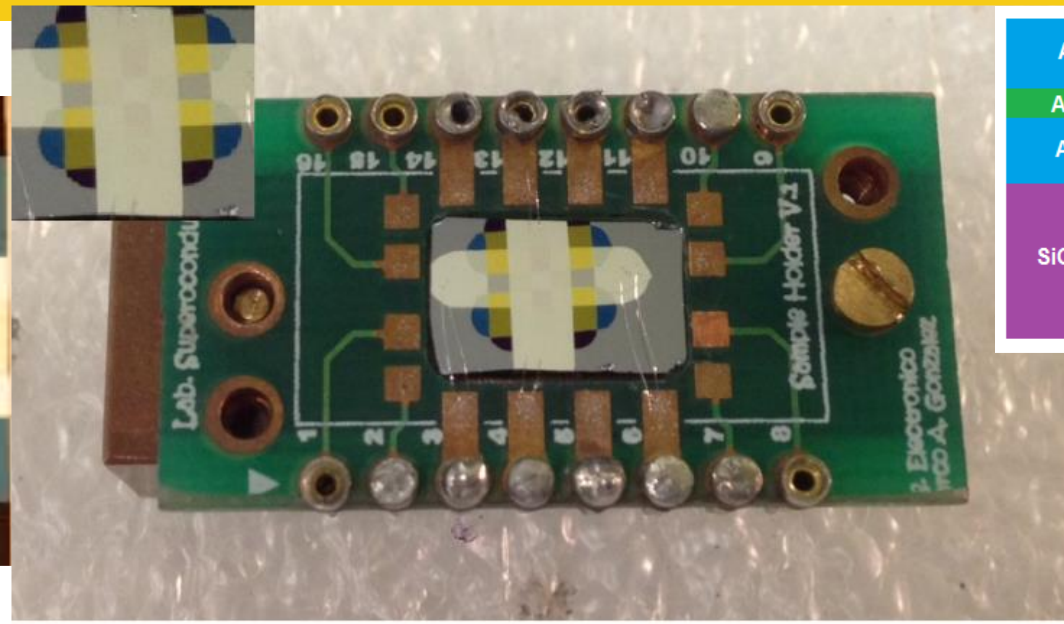


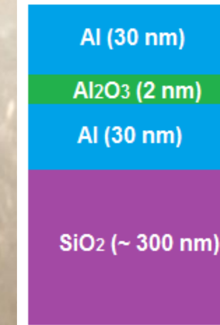


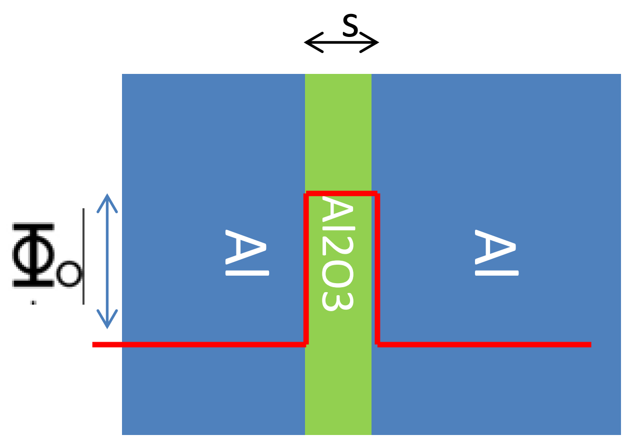
These structures can be fabricated utilizing mechanical masks or standard optical lithography techniques

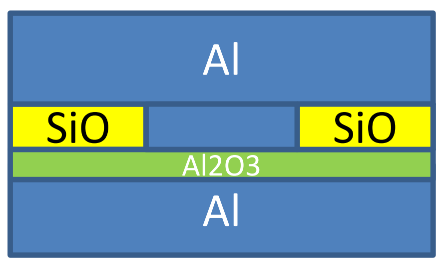
Tunnel junctions: Our experiment











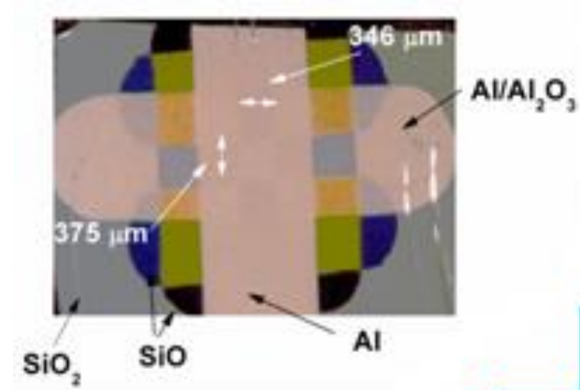


Figure 3: Photograph of planar junctions made using a mask evaporation technique in the system shown in figure. 1.

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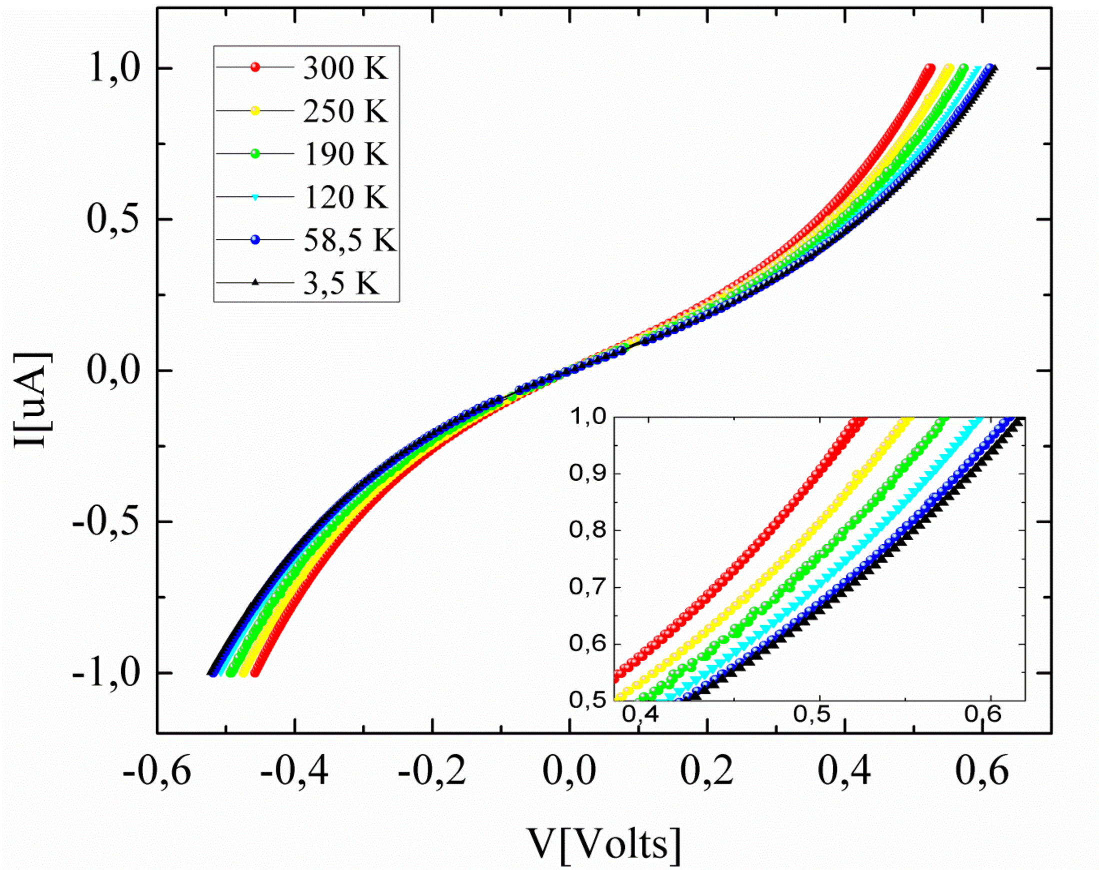
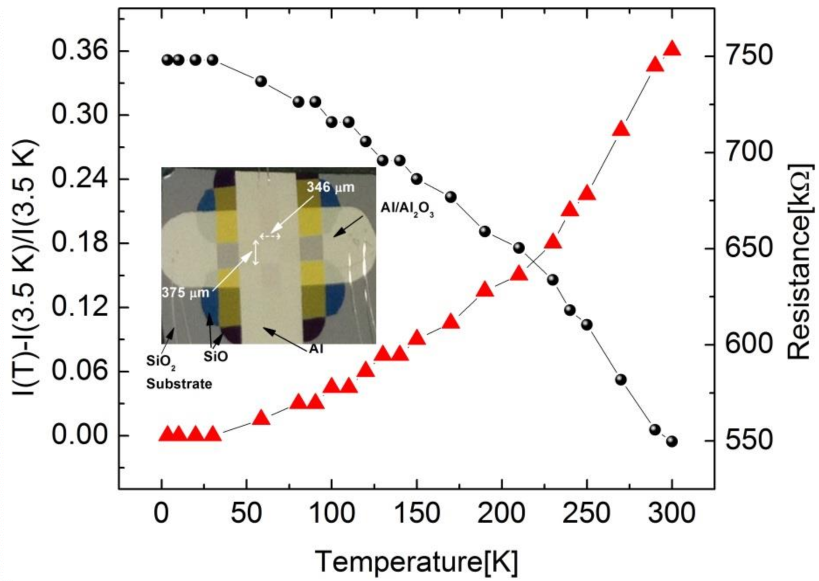
What are the results?



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

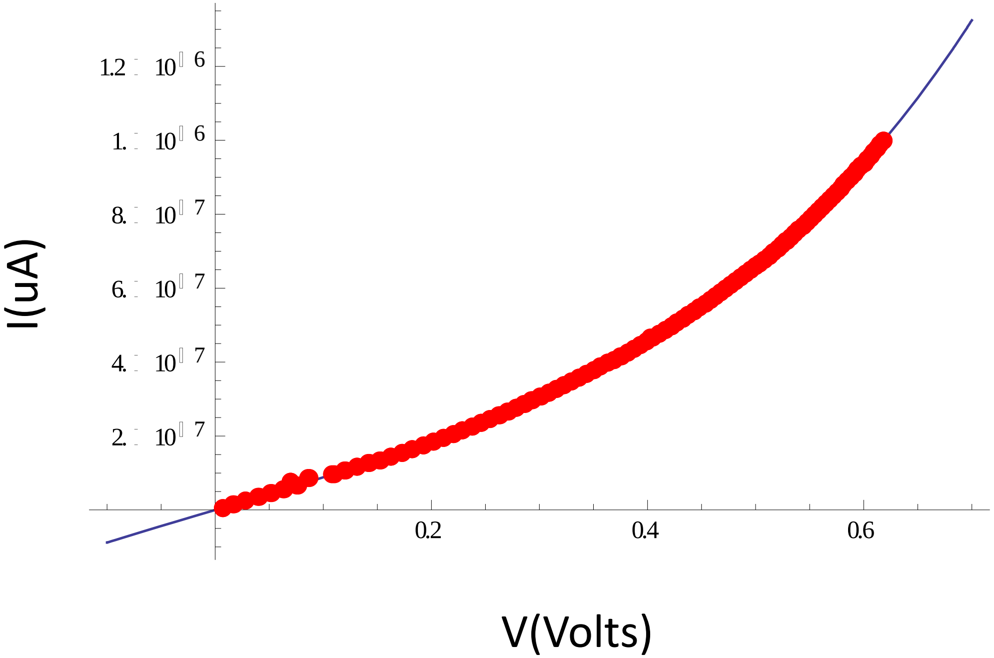


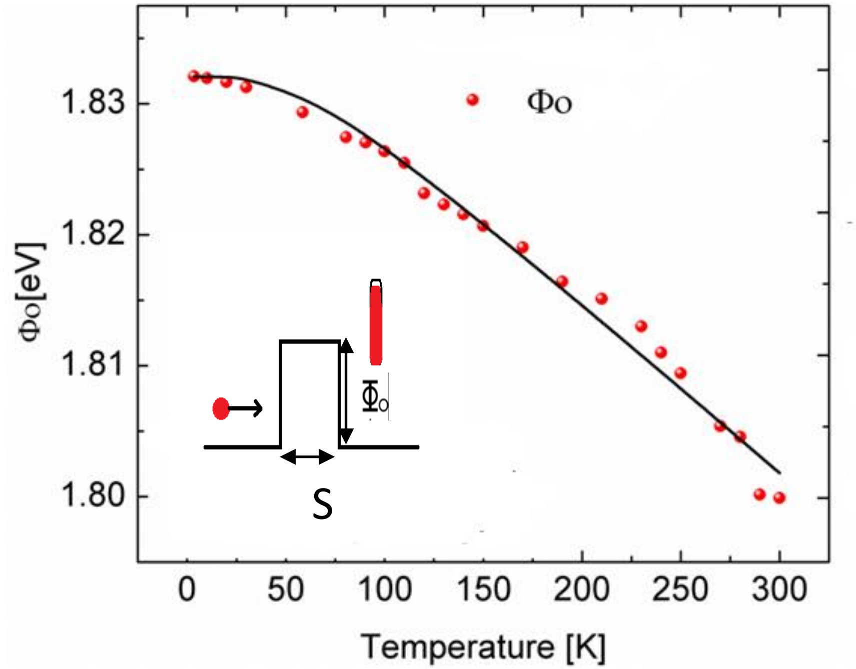
Junction Resistance (triangles) and Tunneling current variation (circles) vs temperature at a bias voltage of 0.5 V

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.

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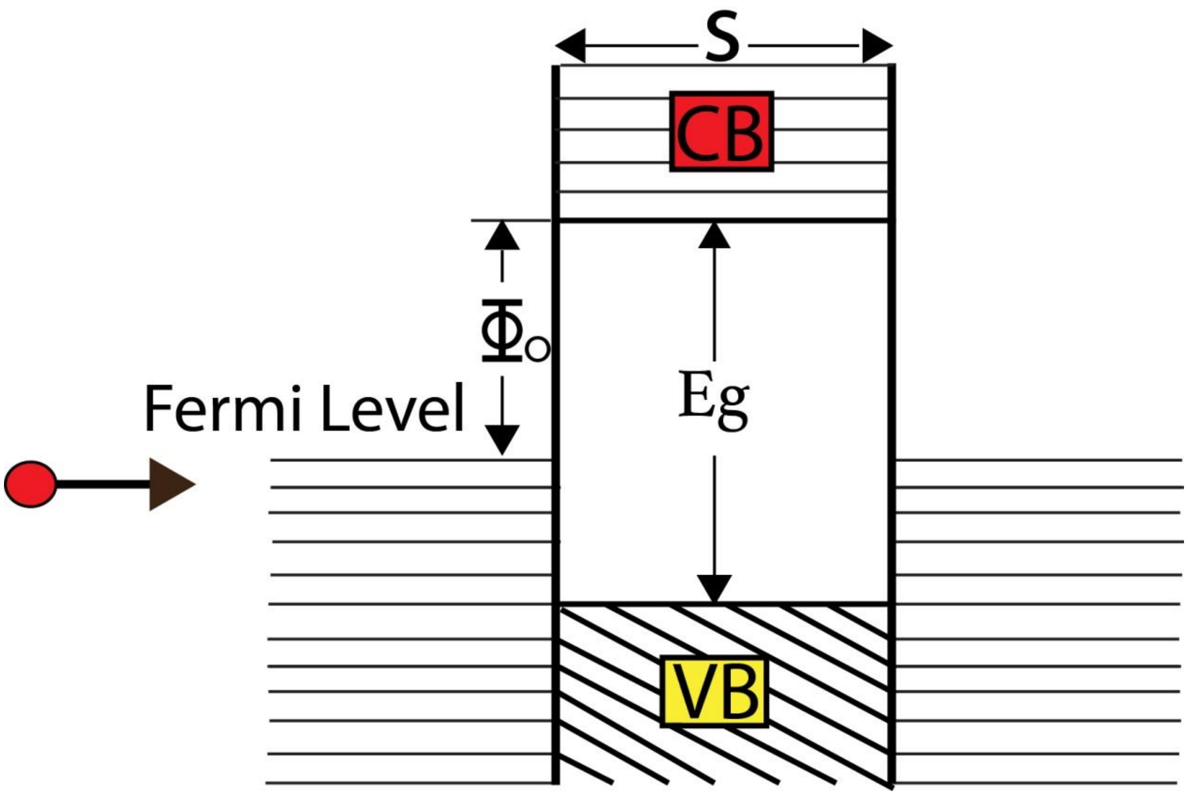
Why is Φ_o changing with temperature ?



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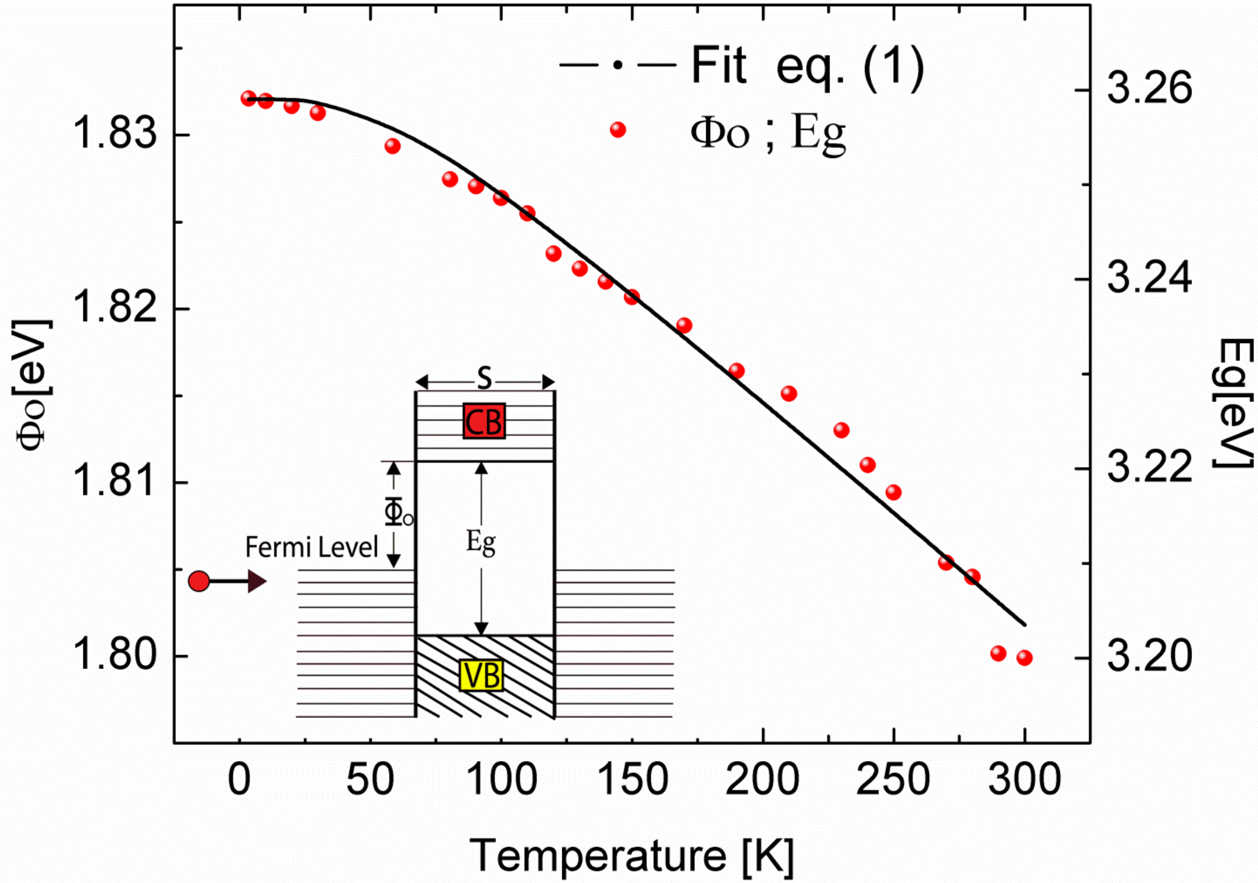
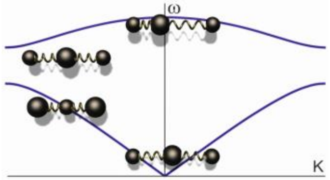
Eq. 1 $$Eg(T) = Eg(0) - S\langle\hbar\omega\rangle[\coth(\langle\hbar w\rangle/2kT) - 1]$$





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

↓

Eq. 1

↓

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

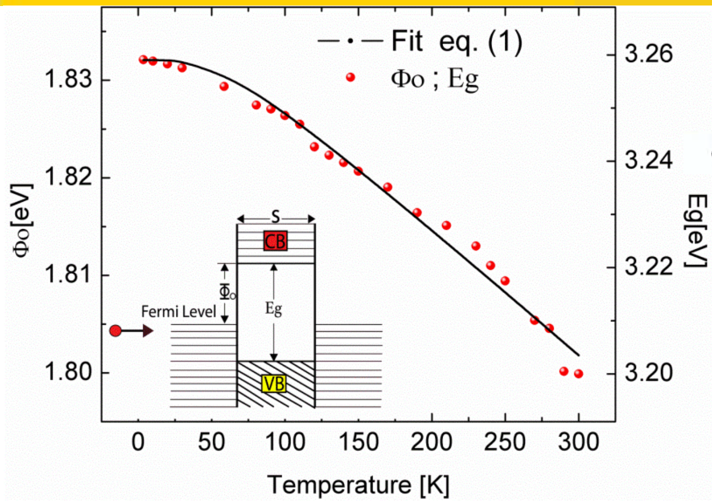
↓

Avg[ω] = 2.05x 10^{13} sec^{-1}

Comparing with speed of sound experiments → ω = 2.24 x 10^{13} sec^{-1} is obtained !

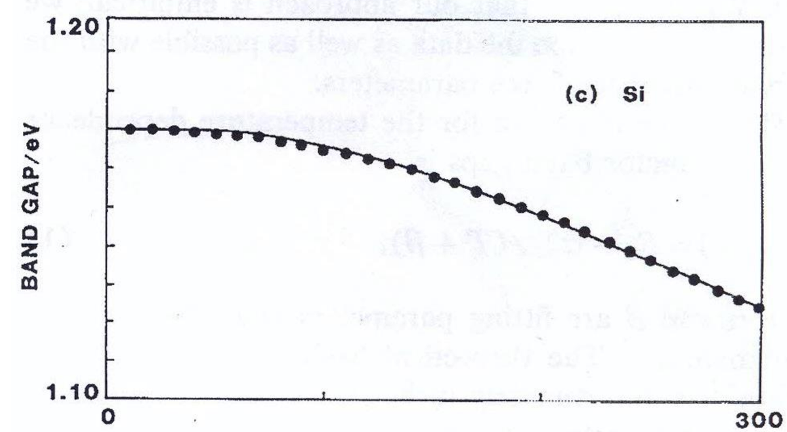
Eq.1:O'Donnell, K. P. and X. Chen (1991). "Temperature dependence of semiconductor band gaps." Applied Physics Letters 58(25): 2924-2926.

Comparing with other semiconductors: O'Donnel

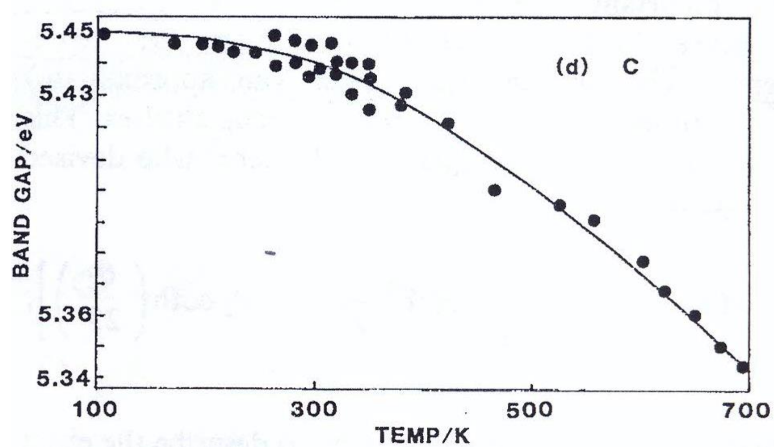


	Estimate	Standard Error
Ego	3.24348	0.00072269
S	1.16311	0.0613627
$\langle \hbar w \rangle$	0.0170526	0.00235379

↑ **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	-

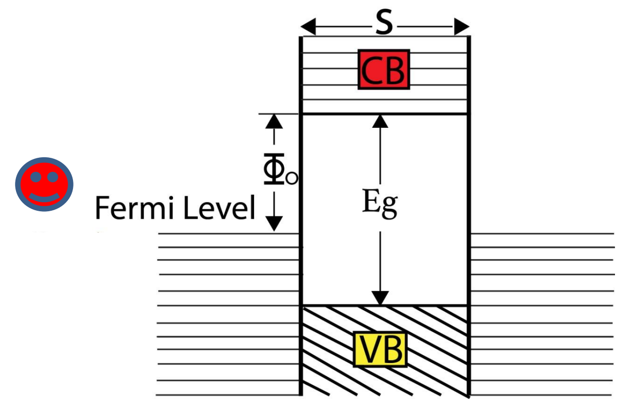


[14]O'Donnell, K. P. and X. Chen (1991). "Temperature dependence of semiconductor band gaps." Applied Physics Letters 58(25): 2924-2926.

Tunneling Time

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

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Tunneling Time (Dwell Time)

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 x 10^{-15} s

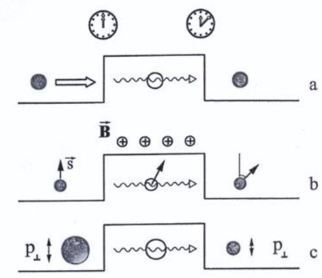

FIG. 1. The idea of the Larmor clock tunneling time measurement. One should invent a clock that starts to measure at the beginning of the barrier crossing and finishes at the end (a). Particle spin vector *s* rotation in the perpendicular magnetic field **B**, superimposed in the barrier region (b),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

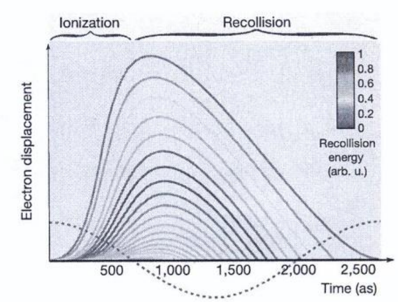

Figure 1 | Electron trajectories contributing to the recollision process. The coloured lines represent the spatio-temporal description of various trajectories; each colour encodes a recolliding energy, increasing from red to blue. The black dashed line shows the electric field along the cycle. arb. u.,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

REPORTS

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

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)

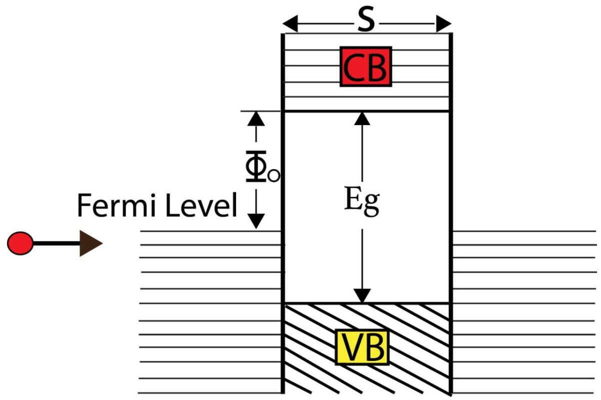
$$\tau_D(E) = \frac{\int_{x_1}^{x_2} |\Psi(x)|^2 \, dx}{j}, \qquad \text{Eq. 1}$$

$x_1, x_2,$ are the classical turning points

momentum ⇩

$$j = \hbar k / \mu$$ ⇦ *reduced mass*

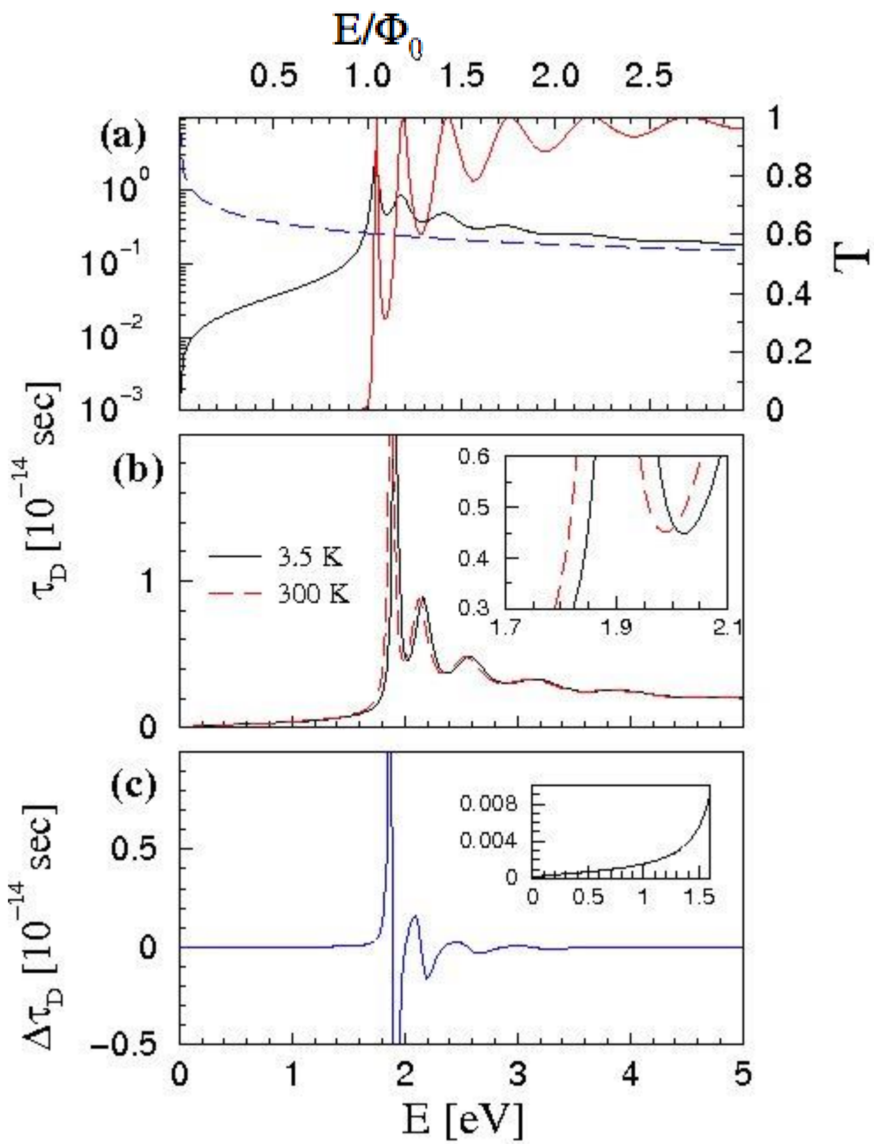
$$k = \sqrt{2mE}/\hbar$$



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 right 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).

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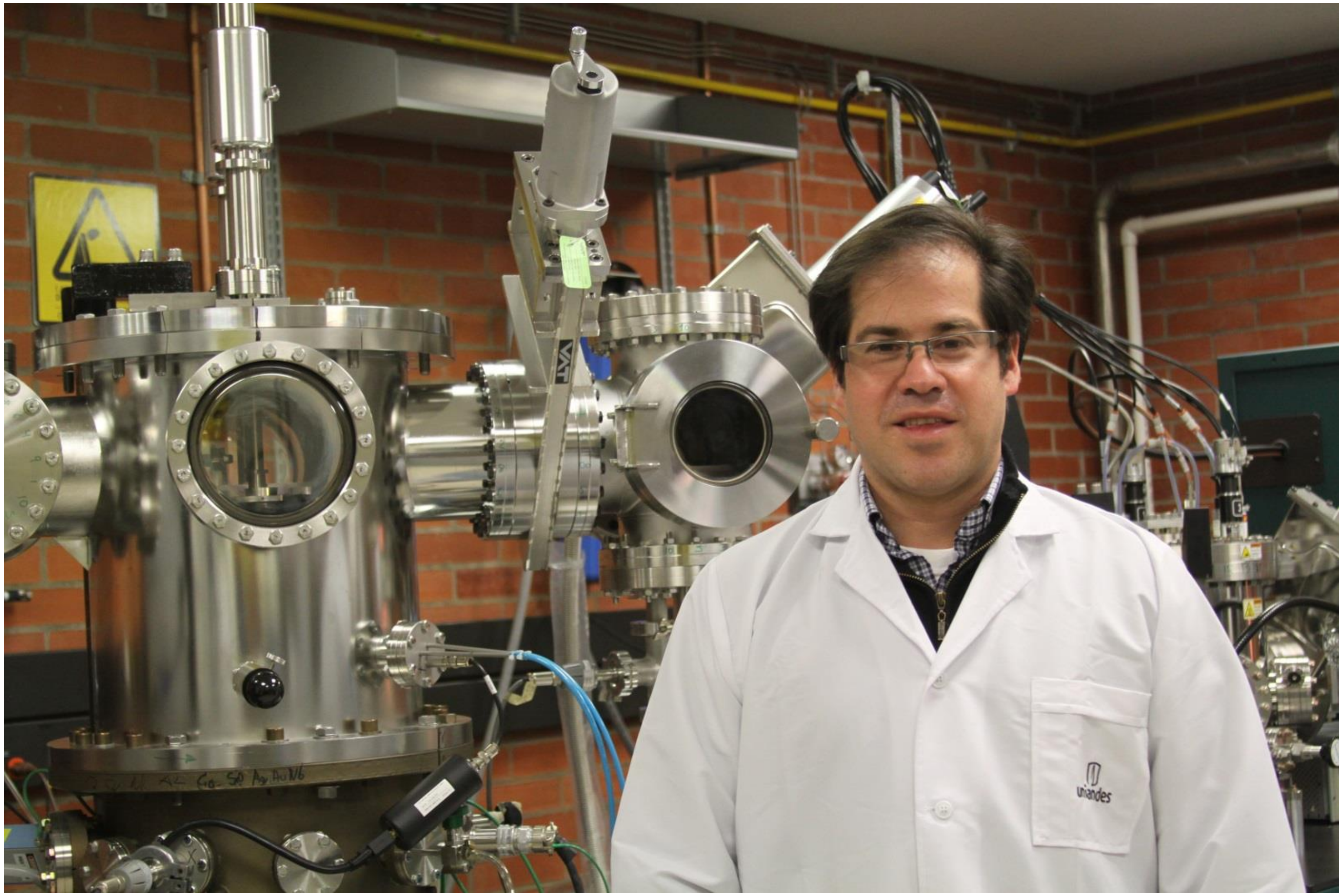
Conclusions

- 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 **$\omega = 2.24 \times 10^{13}\ sec^{-1}$** 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 $Al/Al_2O_3/Al$ junctions**" Applied Physics Letters 107 (25) 2015

Gracias!



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