The charge transport mechanism and the nature of traps in charge trap flash, ReRAM and FeRAM devices

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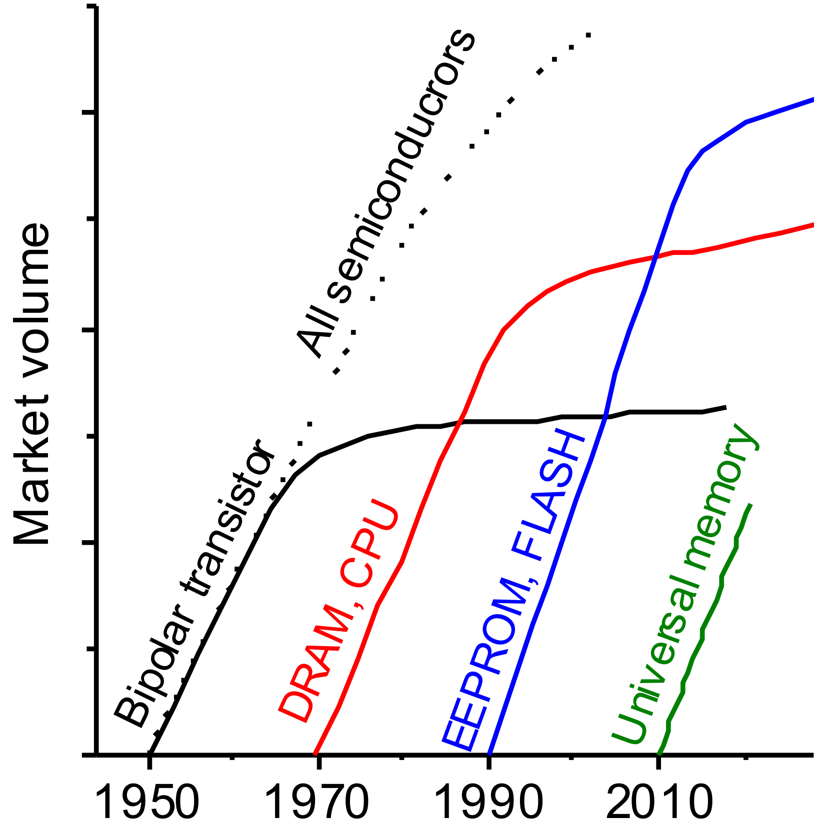
Outlook

- Motivation for the trap nature and charge transport understanding: flash and universal memory
- Defect and trap nature in Si_3N_4
- Defect and trap nature in Al_2O_3
- Defect and trap nature in HfO_2 and ZrO_2
- Defect and trap nature in $Hf_{0.5}Zr_{0.5}O_2$
- Conclusion

History of semiconductor business



Decade	New technology	Replaced technology	Market
1950	Bipolar transistor	Vacuum tube	Radio, TV
1970	MOS (DRAM)	Magnetic memory	Computer
1990	MOS (FLASH)	Hard disk, floppy disk, CD, DVD	Computer, portable systems
2010	Universal memory	Hard disc, DRAM, FLASH	Computer, portable systems

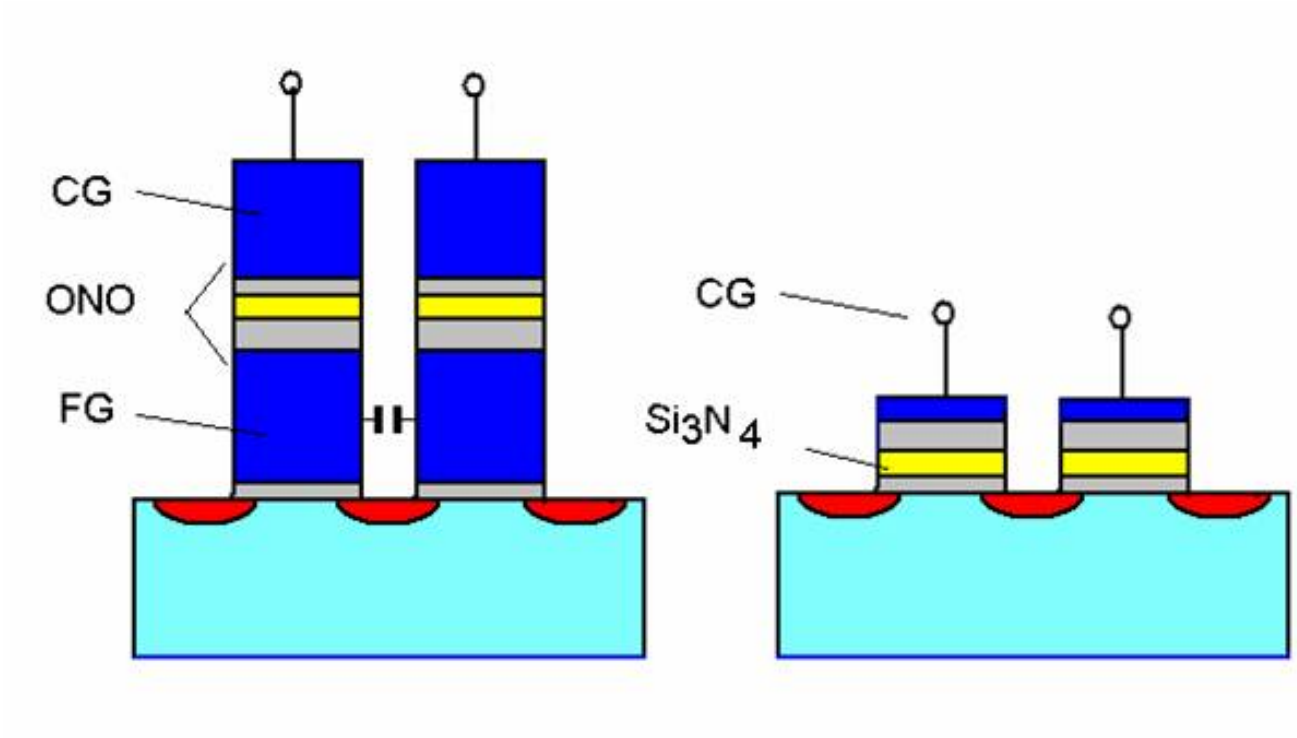
Universal memory

Universal memory combine the advantage's of

- DRAM (high speed, high endurance $>10^{16}$ circles)
- FLASH (non volatility)
- Hard disc (high density, low cost)

Candidates for Universal memory MRAM, FeRAM, ReRAM, PRAM

Scaling of flash memory

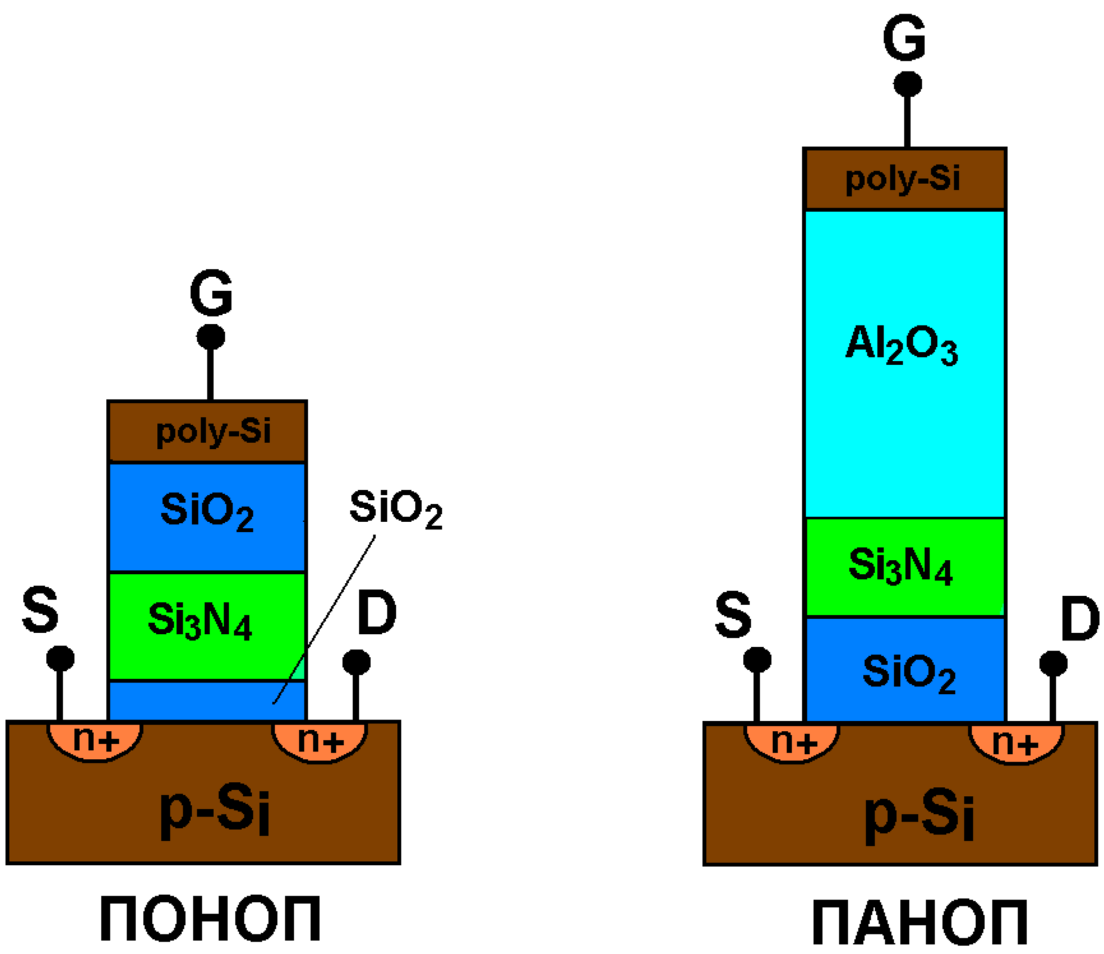


The substantional disadvantage of floating gate flash memory is parasitic interference during information writing.

Interefence results in low reliability of flash memory and restriction for scaling to increase memory volume > 64Gbite.

This disadvantage is overcame in charge trap memory based on Si_3N_4.

High-k dielectric in Charge Trap Flash Memory (CTFM)

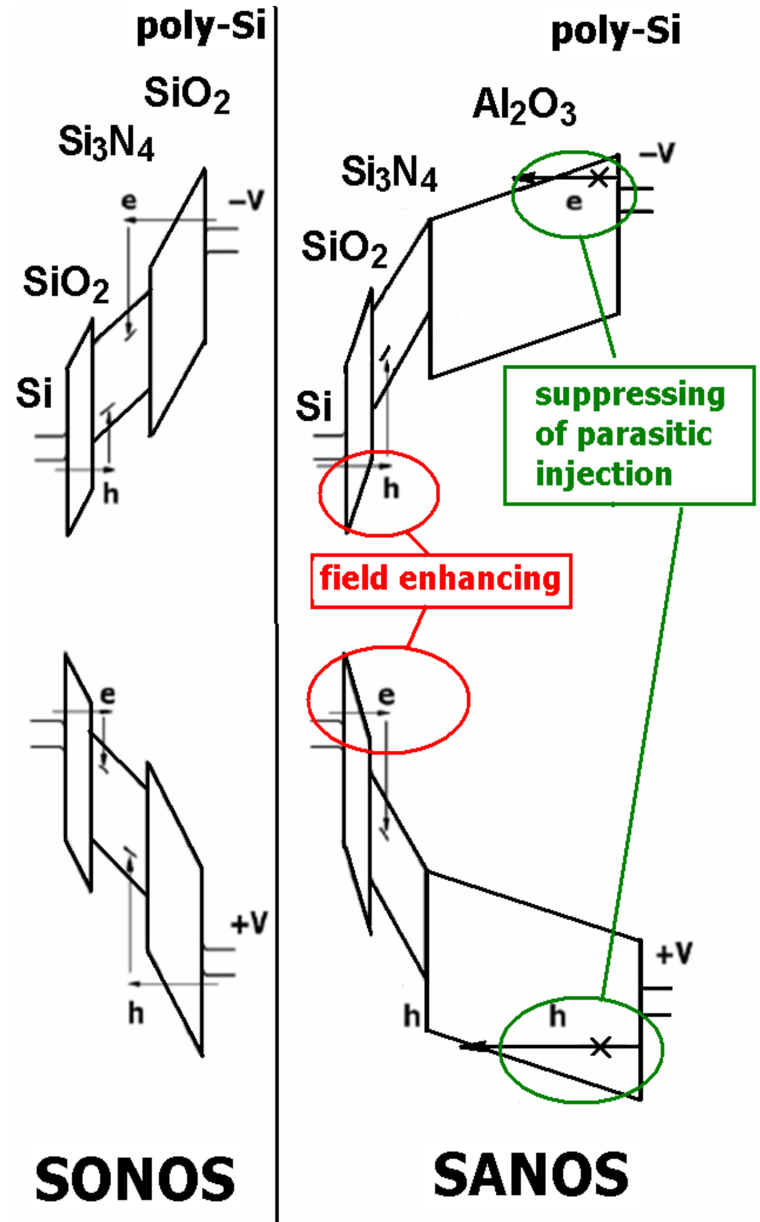


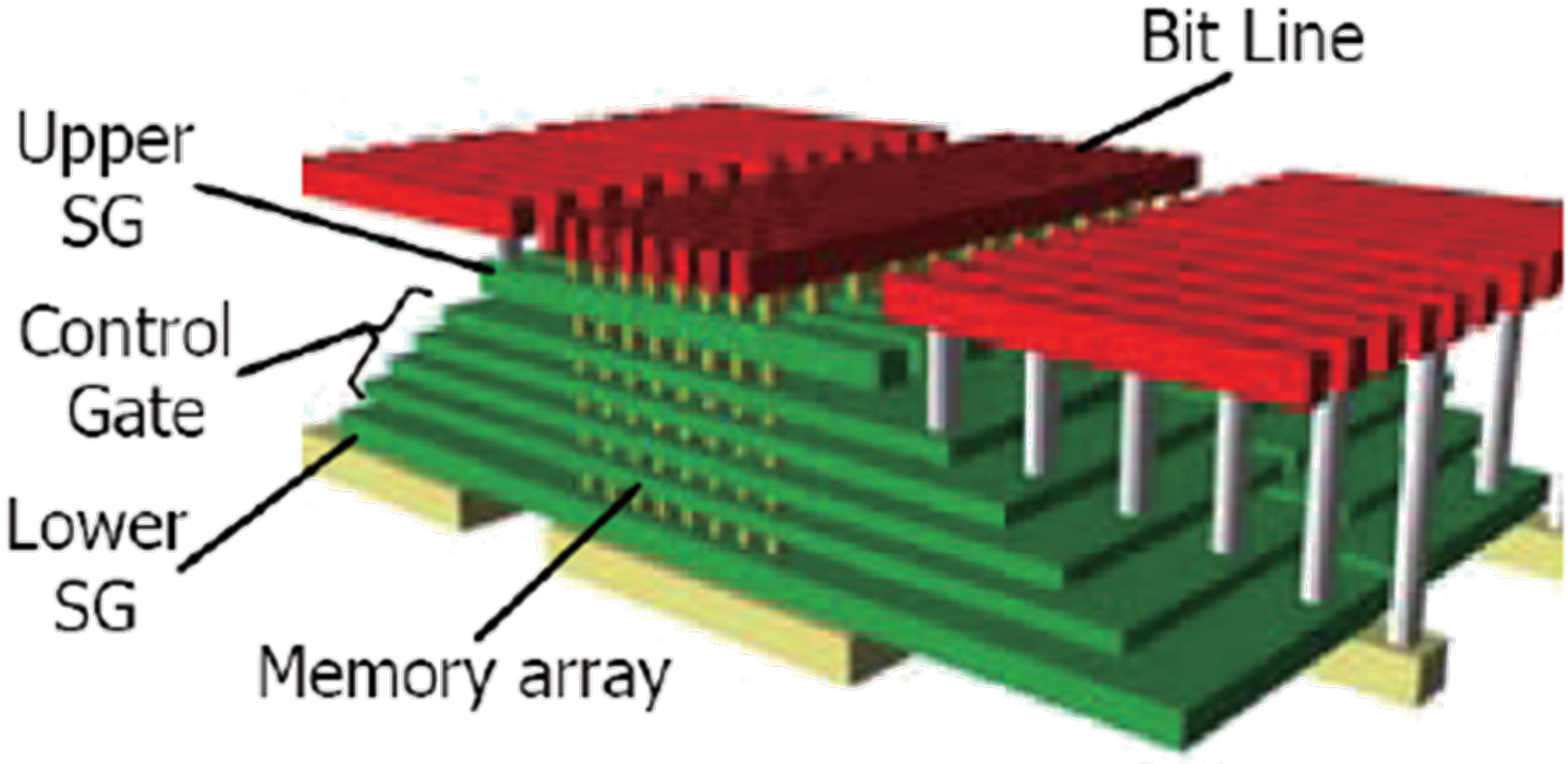
The advantages of the SANOS in comparison with SONOS

The using of high-k dielectrics (with high dielectric constant) as blocking oxide lead to following advantages:

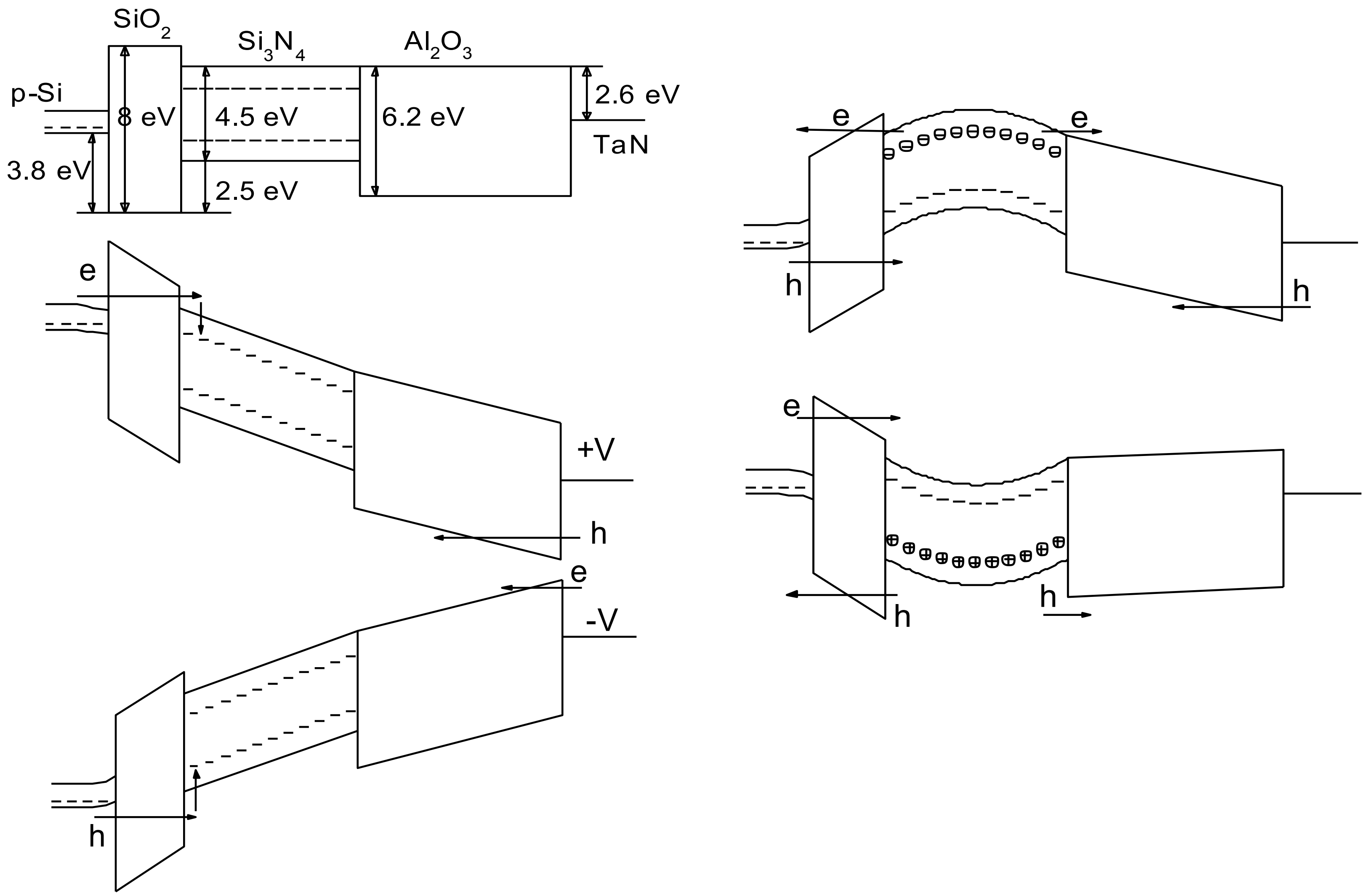
1) the increasing of electric field in the tunnel oxide lead to increasing of current injection (figure on the right hand). This property allows to use thicker tunnel oxide when the memory window is fixed, which can provide the larger retention time i.e. reliability and decrease of rejection rate of flash memory.

2) the decreasing of voltage drop on the blocking oxide leads to decreasing of parasitic injection of electrons and holes form poly silicon gate during write/erase operations (see figure on the right hand)




Bit Line
Upper
SG
Control
Gate
Lower
SG
Memory array

Energy diagram of TANOS memory element



Mathematical model for simulation of flash devices memory properties and charge transport in high-k dielectrics

$$\frac{\partial n(x,t)}{\partial t} = \frac{1}{e}\frac{\partial j(x,t)}{\partial x} - \sigma_r\, \upsilon n(x,t)\big(N_t - n_t(x,t)\big) + n_t(x,t)P^{(n)}(x,t) - \sigma_r \upsilon n(x,t)p_t(x,t)$$

$$\frac{\partial n_t(x,t)}{\partial t} = \sigma \upsilon n(x,t)\big(N_t - n_t(x,t)\big) - n_t(x,t)P^{(n)}(x,t) - \sigma_r \upsilon p(x,t)n_t(x,t)$$

$$\frac{\partial p(x,t)}{\partial t} = \frac{1}{e}\frac{\partial j_p(x,t)}{\partial x} - \sigma v p(x,t)\big(N_t - p_t(x,t)\big) + p_t(x,t)P^{(p)}(x,t) - \sigma_r v p(x,t)n_t(x,t)$$

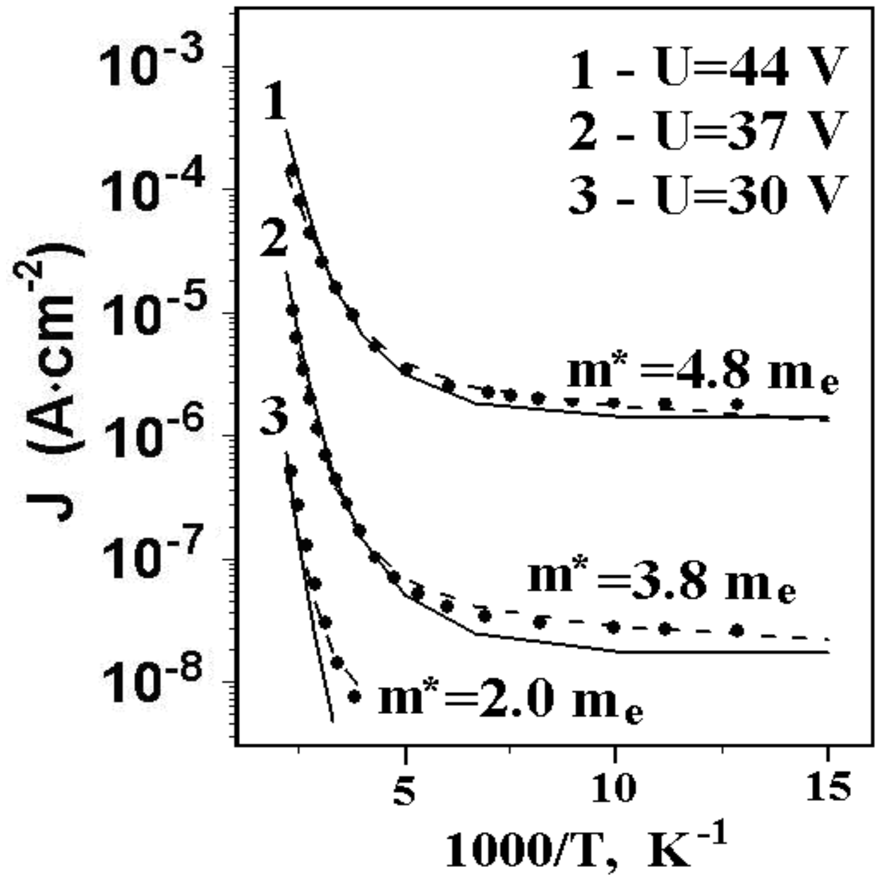
$$\frac{\partial p_t(x,t)}{\partial t} = \sigma \upsilon p(x,t)\big(N_t - p_t(x,t)\big) - p_t(x,t)P^{(p)}(x,t) - \sigma_r \upsilon p(x,t)n_t(x,t)$$

$$\frac{\partial F}{\partial x} = -e\frac{(n_t(x,t) - p_t(x,t))}{\varepsilon\varepsilon_0}$$

$$P = \sum_{n=-\infty}^{+\infty}\exp\left[\frac{nW_{ph}}{2kT} - S\coth\frac{W_{ph}}{2kT}\right]I_n\left(\frac{S}{\sinh(W_{ph}/2kT)}\right)P_i(W_T + nW_{ph})$$

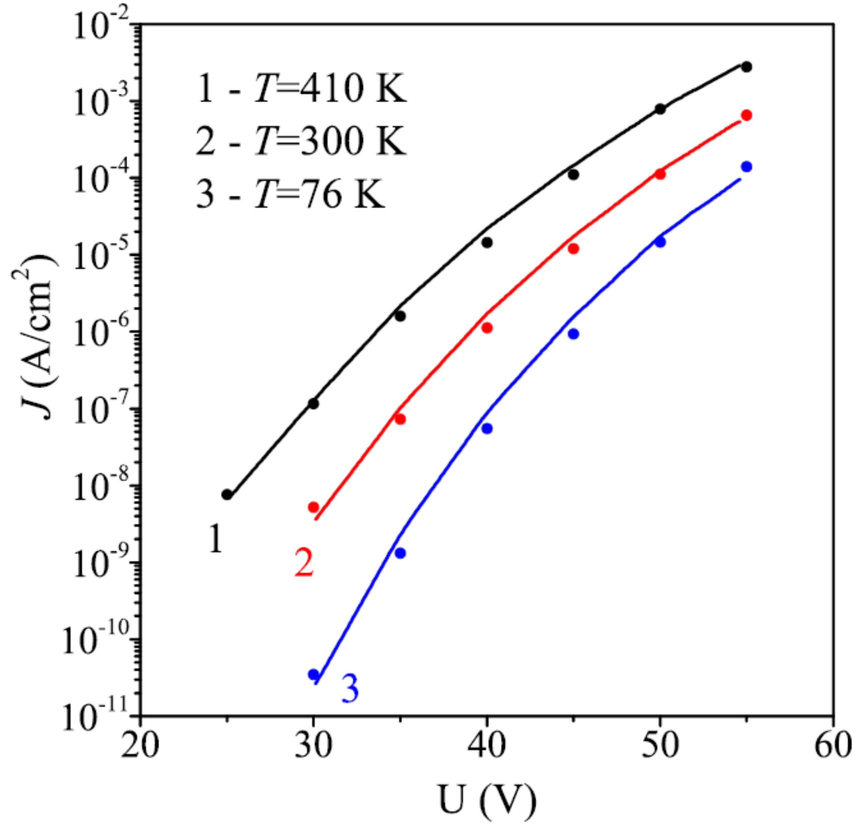
$$P_i(W) = \frac{eF}{2\sqrt{2m^*W}}\exp\left(-\frac{4}{3}\frac{\sqrt{2m}}{\hbar eF}W^{3/2}\right), \qquad S = \frac{W_{opt} - W_T}{W_{ph}}$$

Current as function of temperature in silicon nitride: experiment and simulation: Frenkel Model



K. A. Nasyrov, V. A. Gritsenko, M. K. Kim et. al,
Charge Transport Mechanism in Metal-Nitride-Oxide Silicon Structures,
IEEE Electron Device Letters, V. 23, p. 336, 2002.

Current-voltage characteristics of memory node-silicon nitride in TANOS: Multiphonon Model

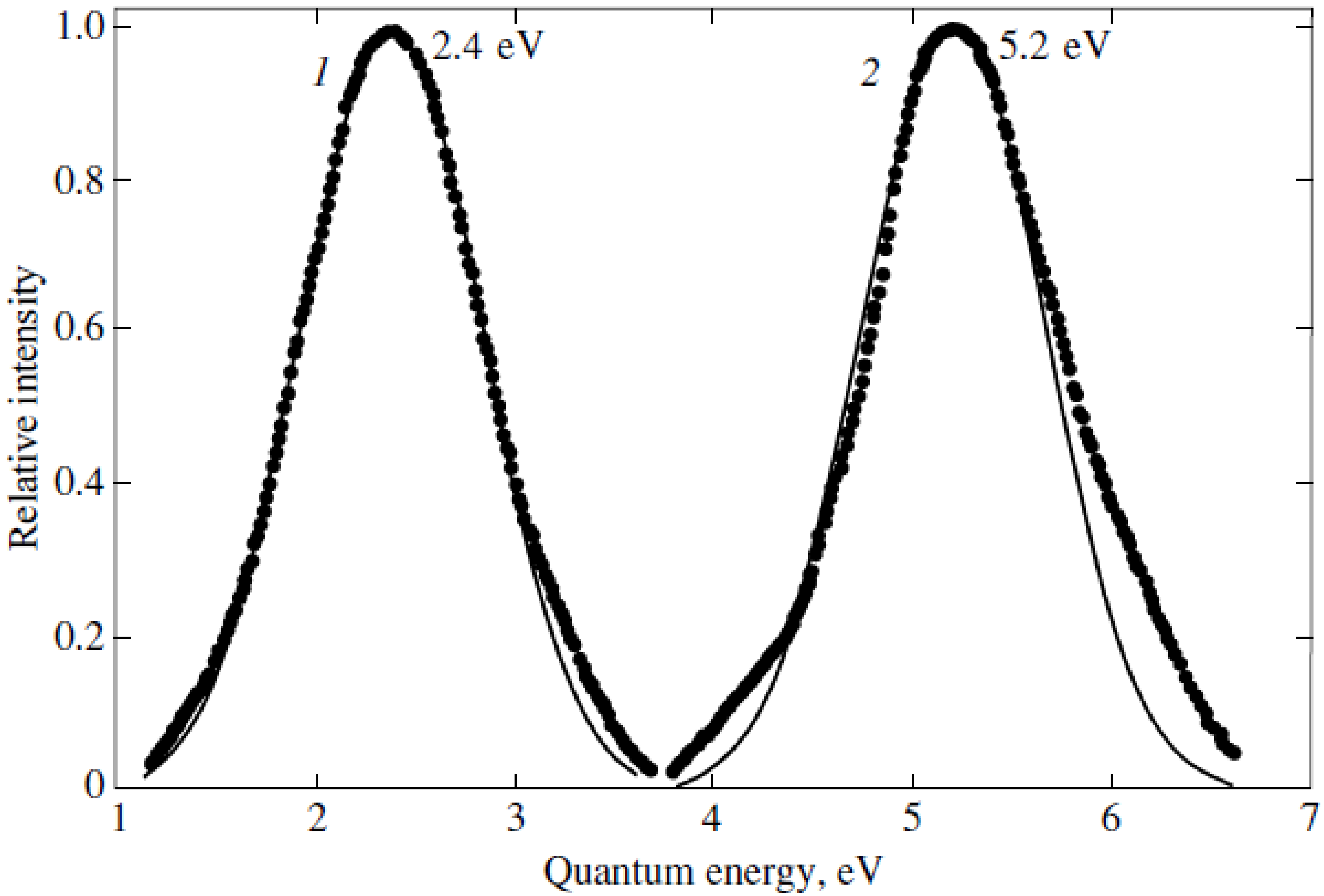


W_t=1.4 eV

W_{opt}=2.8 eV

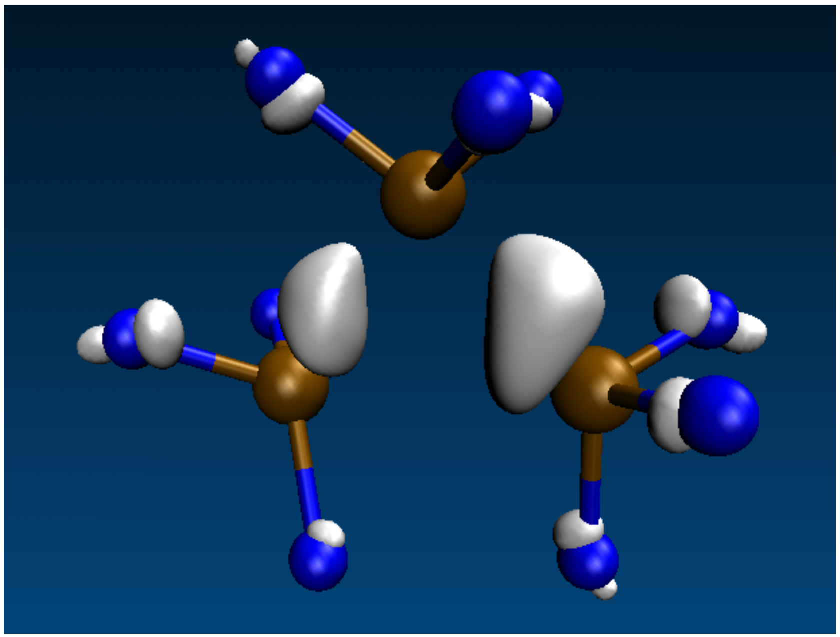
V.A. Gritsenko, N.V. Perevalov, O.M. Orlov, G. Ya. Krasnikov, Nature of Traps Responsible for the Memory Effect in Silicon Nitride, Applied Physics Letters, v. 109, p. 06294, 2016

Photoluminescence of Si_3N_4

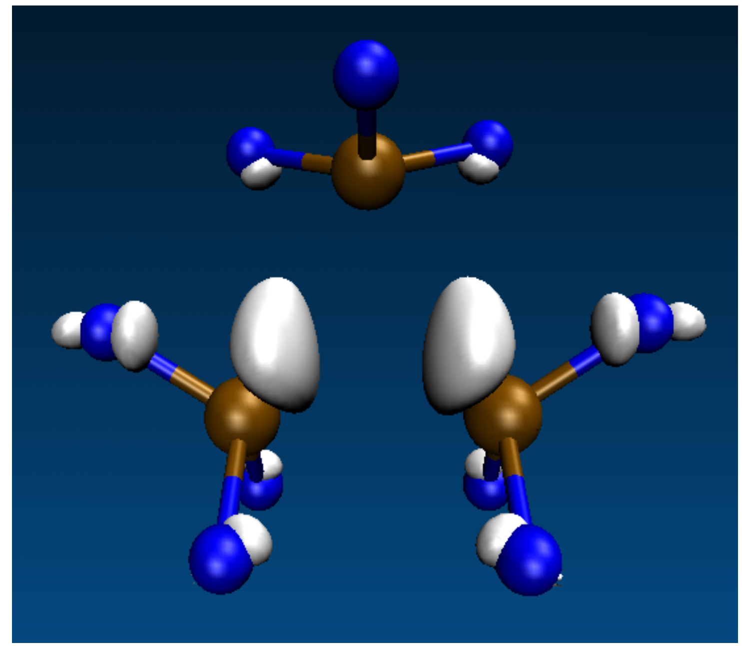


Nature of memory traps in silicon nitride of flash devices

Electron localization



Hole localization



S.S. Nekrashevich, V.V. Vasilev,A.V. Shaposhnikov, V.A. Gritsenko, Electronic structure of memory traps in silicon nitride, Microelectronic Engineering **86**, p.1866, 2009.

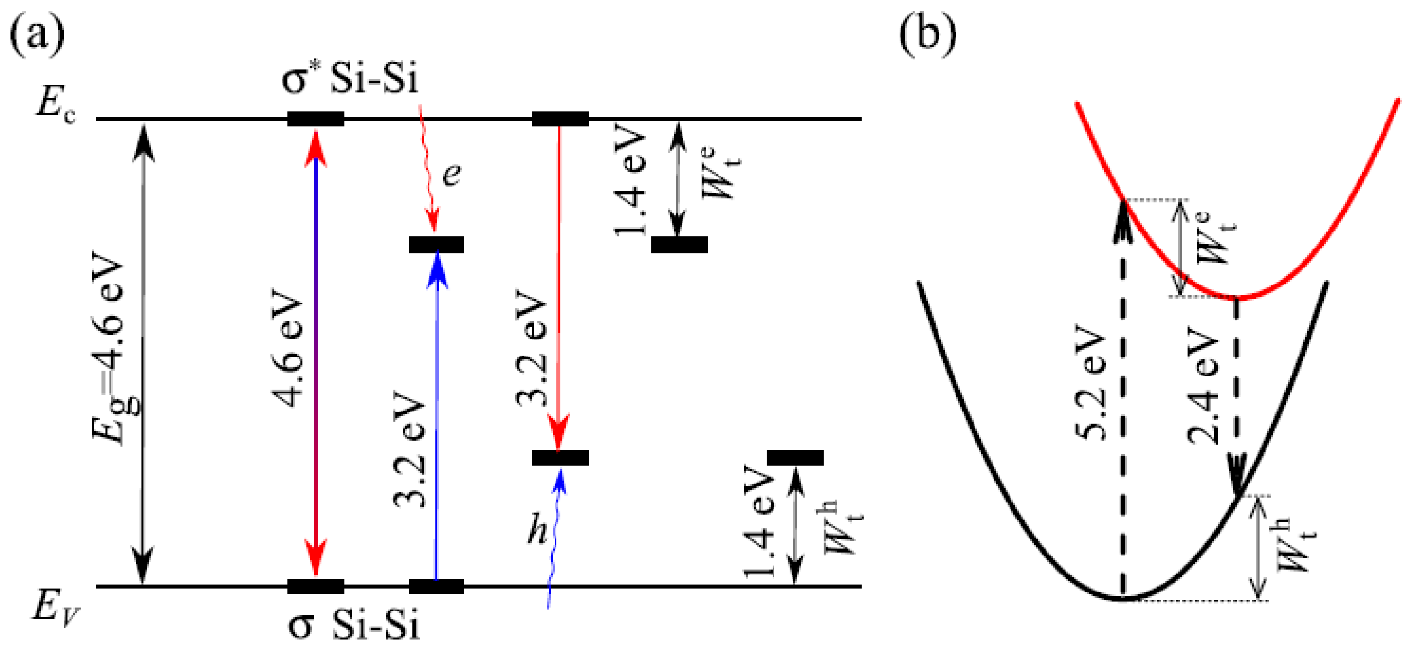
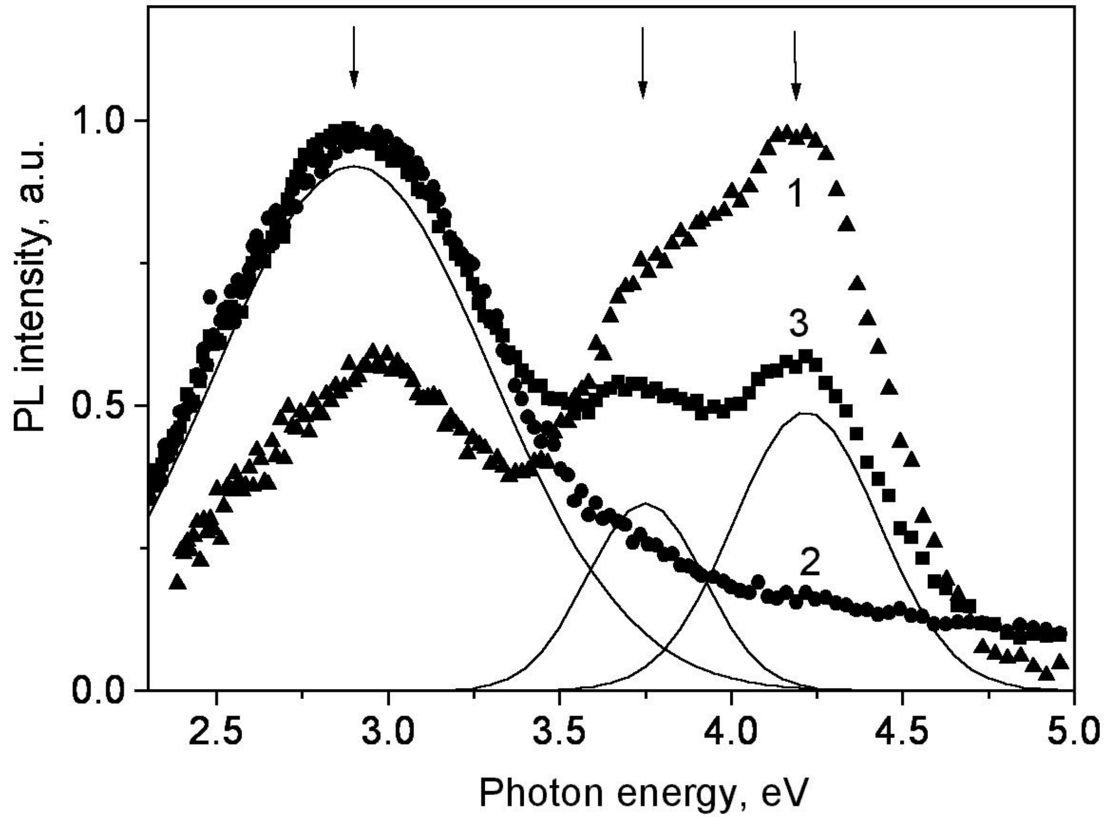


FIG. 5. (a) The energy diagram of electronic transitions in the Si–Si bond in Si_3N_4 associated with the UV PL. (b) A configuration diagram of the optical transitions related to the 2.4 eV green photoluminescence line in Si_3N_4.

$W_t^e = W_t^h = 1.4$ eV is equal to half of PL shift (5.2-2.4)/2=1.4 eV

V.A. Gritsenko, N.V. Perevalov, O.M. Orlov, G. Ya. Krasnikov, Nature of Traps Responsible for the Memory Effect in Silicon Nitride, Applied Physics Letteres, v. 109, p. 06294, 2016

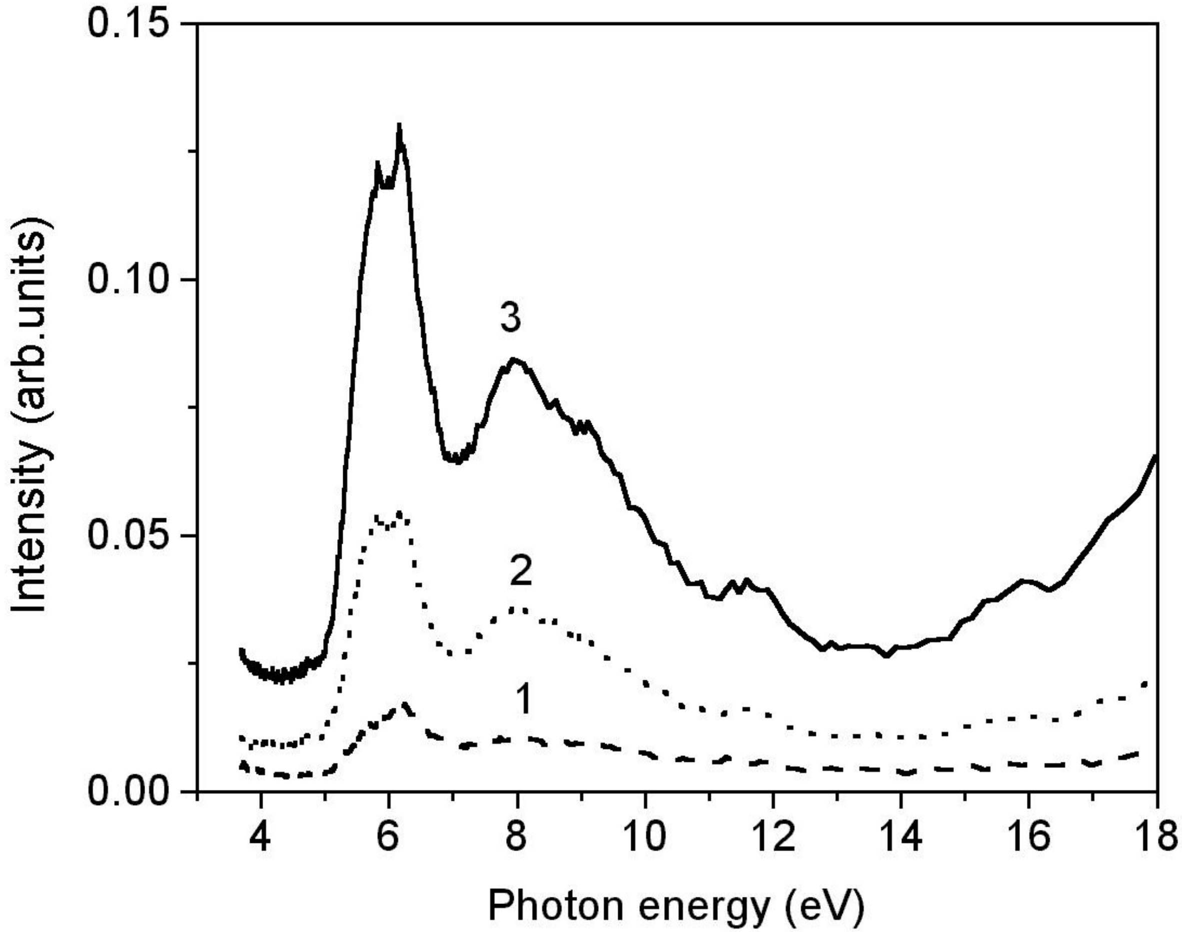
Ptotoluminescence of Al_2O_3 exited by synchrotron radiation



Photoluminescence energy indicate on existence of oxygen vacancies in Al_2O_3

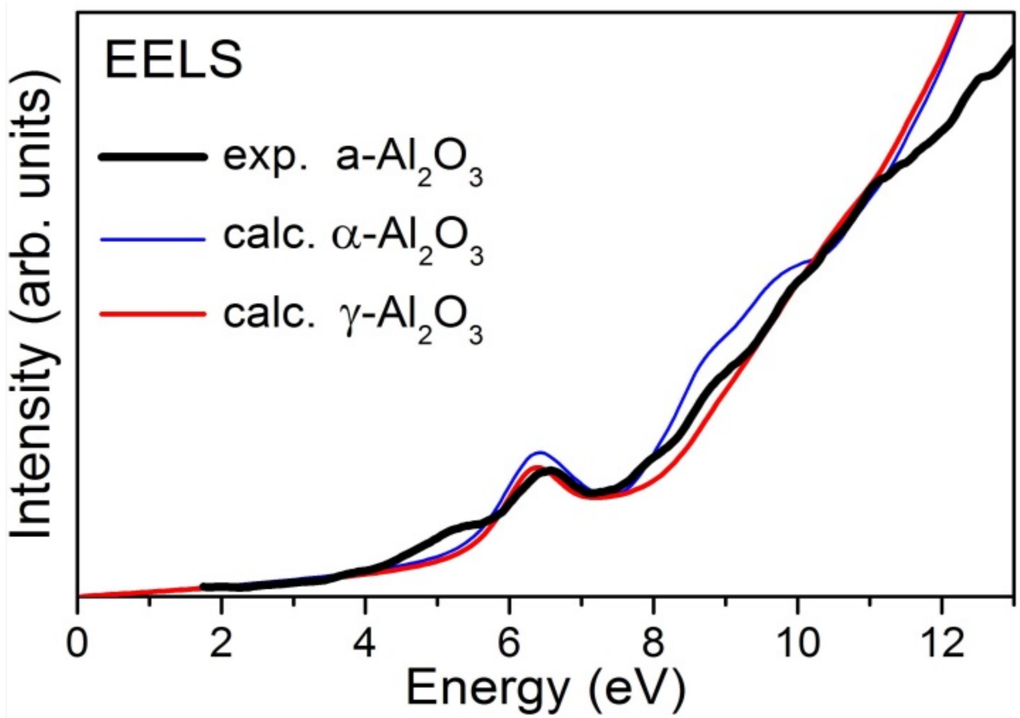
T.V. Perevalov, O.E. Tereshenko, V.A. Gritsenko, V.A. Pustovarov et. al,
Oxygen Deficiency Defects in Amorphous Al_2O_3,
J. Appl. Phys. v.108, p.013501, 2010.

Excitation spectra of oxygen vacancy in Al_2O_3



Luminescence Stokes shift 6.0-3.0=3.0 eV

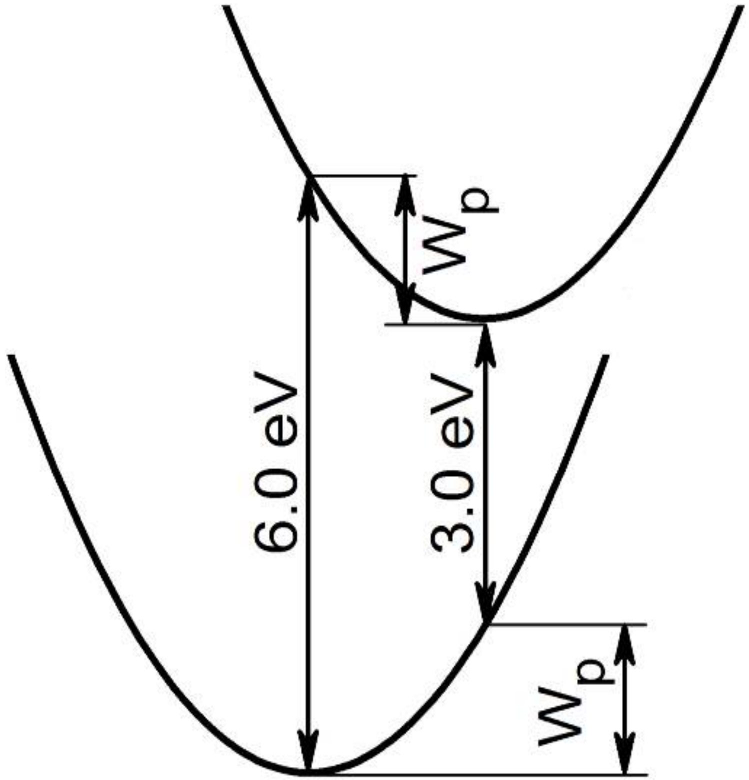
Electron Energy Loss Spectroscopy of Al_2O_3



Experimental EELS spectra for a-Al_2O_3 (black line) and calculated one for α- and γ-Al_2O_3 with oxygen vacancy.

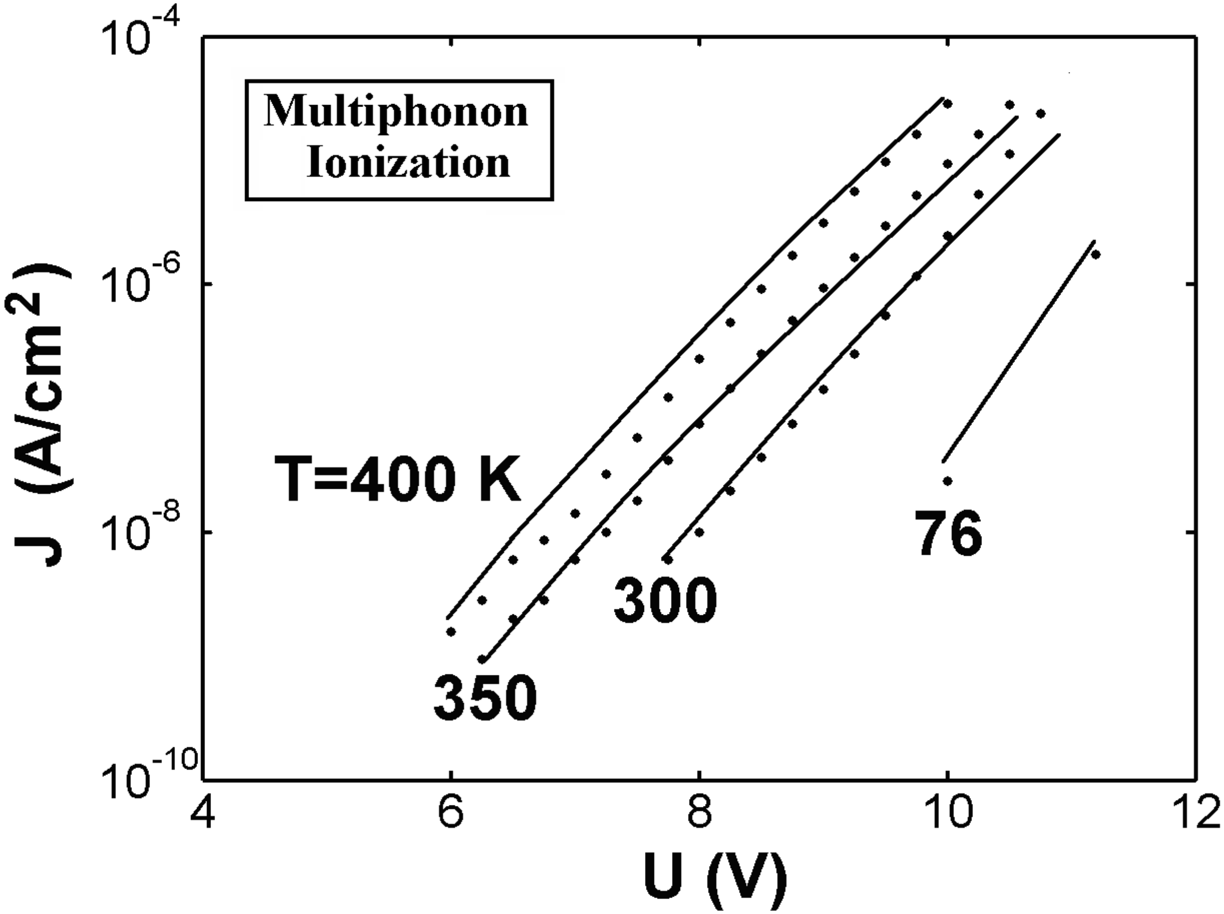
T.V. Perevalov, A.V. Shaposhnikov, V.A. Gritsenko, Electronic structure of bulk and defects α- and γ-Al_2O_3, Microelectronic Engineering, **86**, 1915, March, 2009.

Configuration diagram of optical transition on oxygen vacancy in Al_2O_3



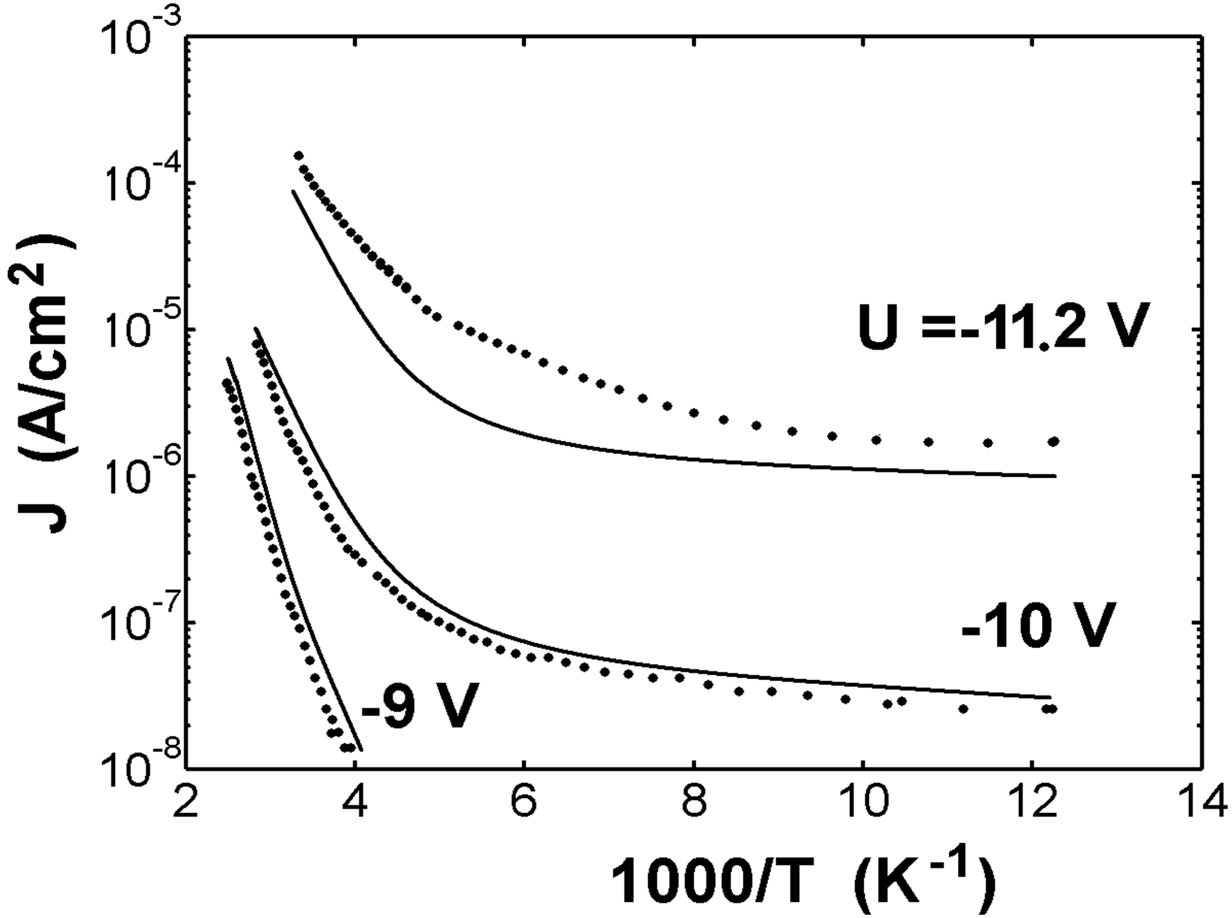
Polaron energy in Al_2O_3 is 1.5 eV

Current voltage characteristics of Al_2O_3: Multiphonon Model



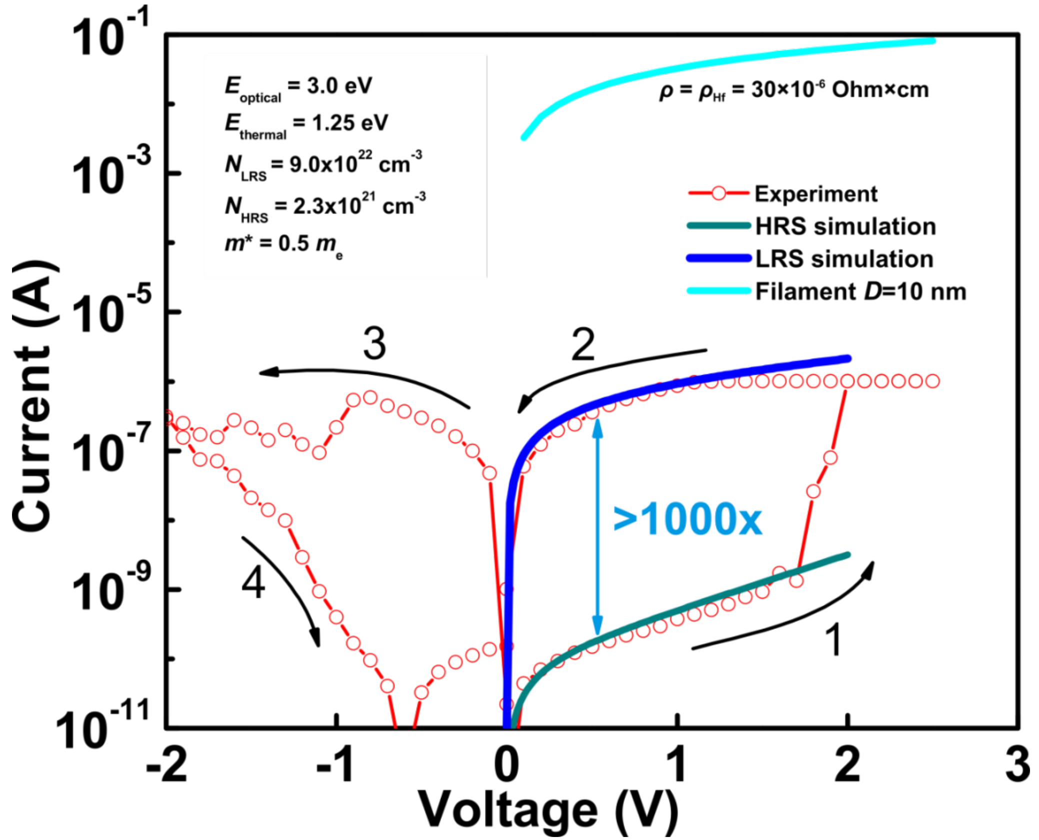
Thermal trap energy Wt=1.5 eV (half of Stokes shift)

Current versus temperature in Al_2O_3



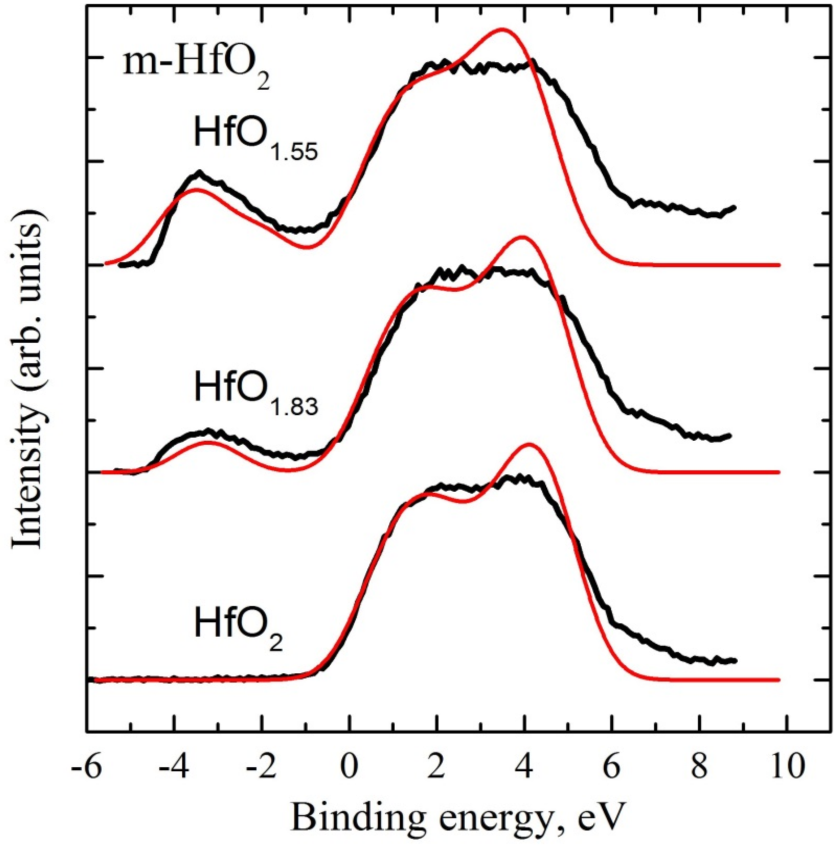
N. Novikov, V.A. Gritsenko, K.A. Nasyrov,
Charge transport mechanism in amorphous alumina,
Appl. Phys. Lett. v.**94**, p.222904, 2009.

ReRAM TaN/HfO_x-Ni



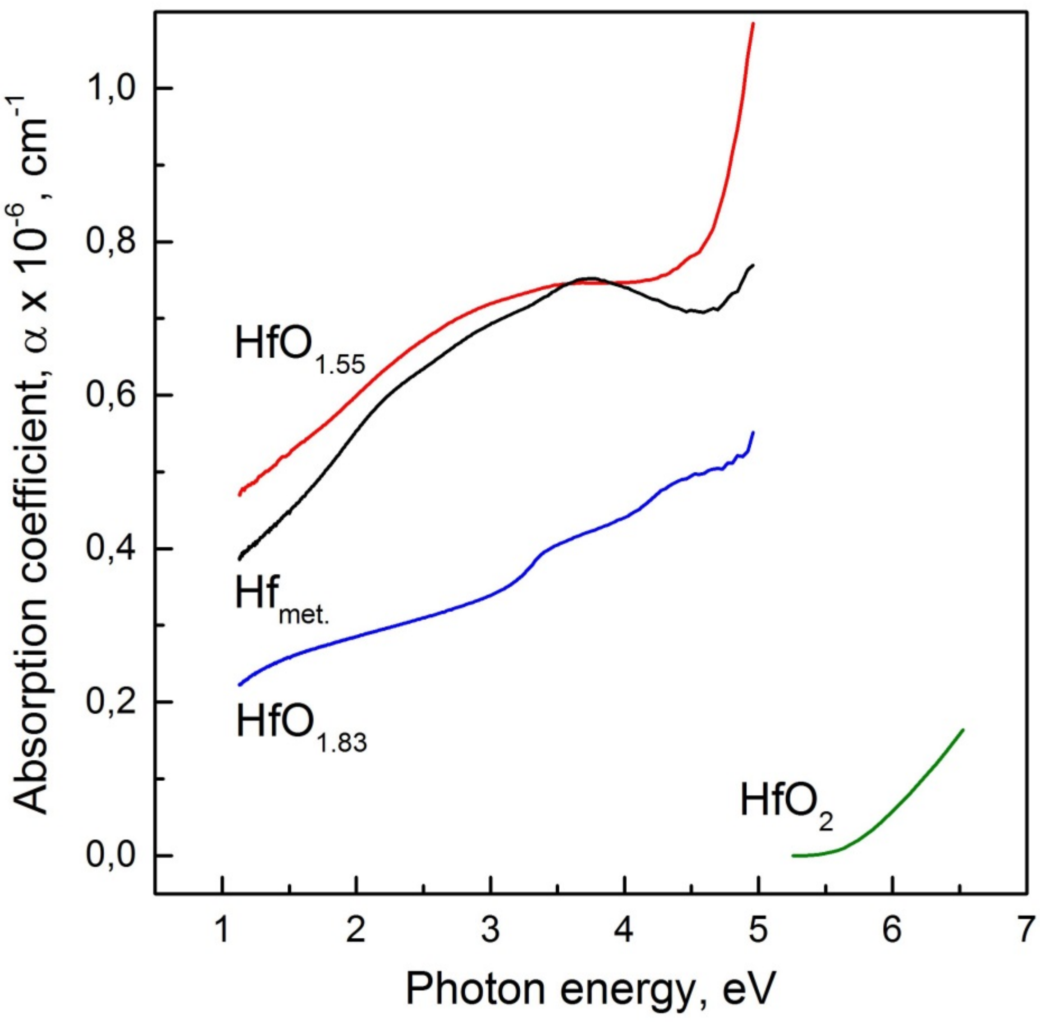
D. R. Islamov, V. A. Gritsenko , C. H. Cheng , A. Chin,
Percolation conductivity in hafnium sub-oxides,
Appl. Phys. Lett. v.105, p.262903, 2014

XPS of valence band in nonstoihiometric HfO_x

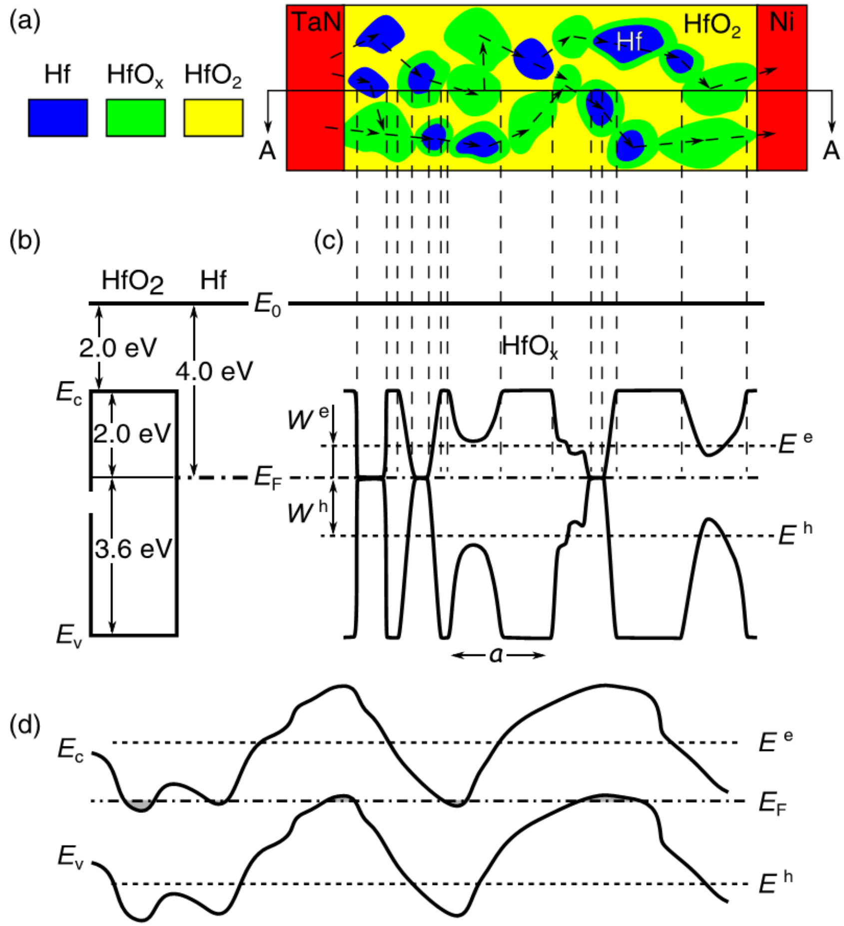


V.N. Kruchinin, V.Sh. Aliev, D.R. Islamov, T.V. Perevalov, V. A. Gritsenko Nanoscale Potential Fluctuation in Non-Stoichiometric HfOx and Low Resistive Transport in RRAM, Microelectronic Engineering v.147, p.165, 2015

Optical absorption in nonstoichiometric HfO_x and HfO_2



Nanoscale potential fluctuations in HfO_x



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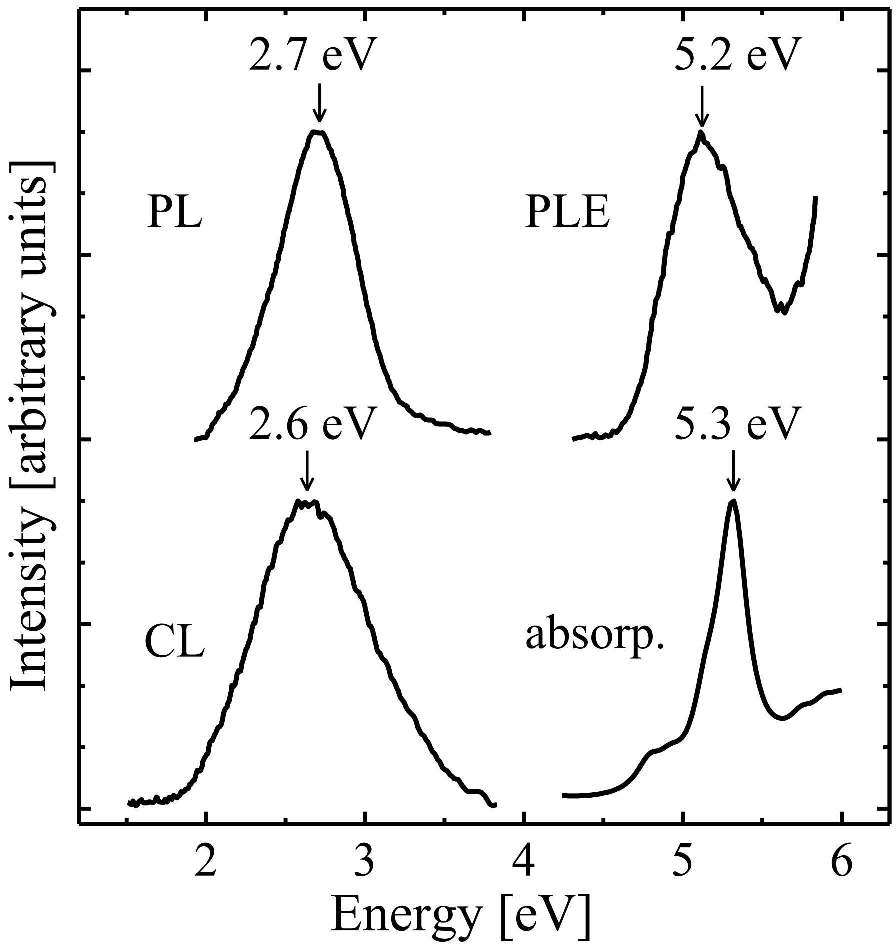
Percolation conductivity in hafnium sub-oxides,
Appl. Phys. Lett. v.105, p.262903, 2014

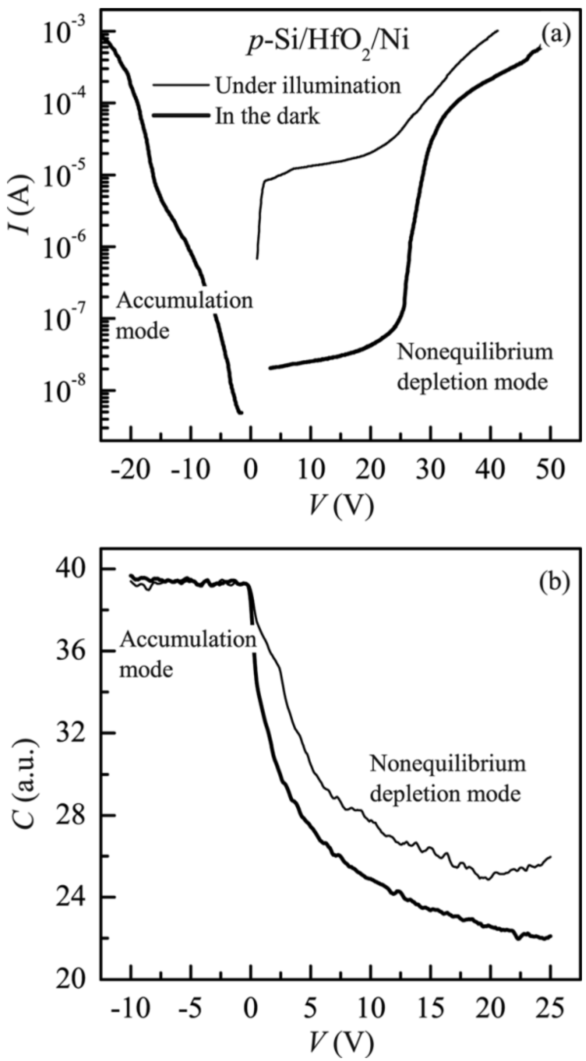
Photoluminescence of nonstoihiometric $HfO_{x<2}$

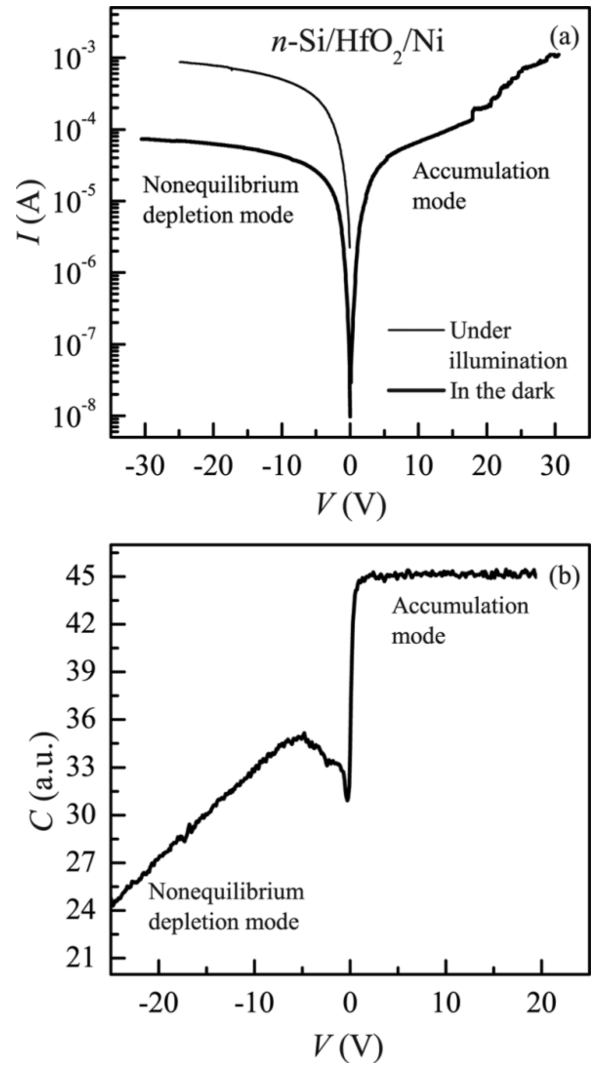


PL and PLE spectra
of the blue 2.7 eV emission
band of $HfO_{x < 2}$

D. R. Islamov, V. A. Gritsenko, C. H. Cheng , A. Chin,
Origin of traps and charge transport mechanism in hafnia,
Appl. Phys. Lett. v.105, p.222901, 2014

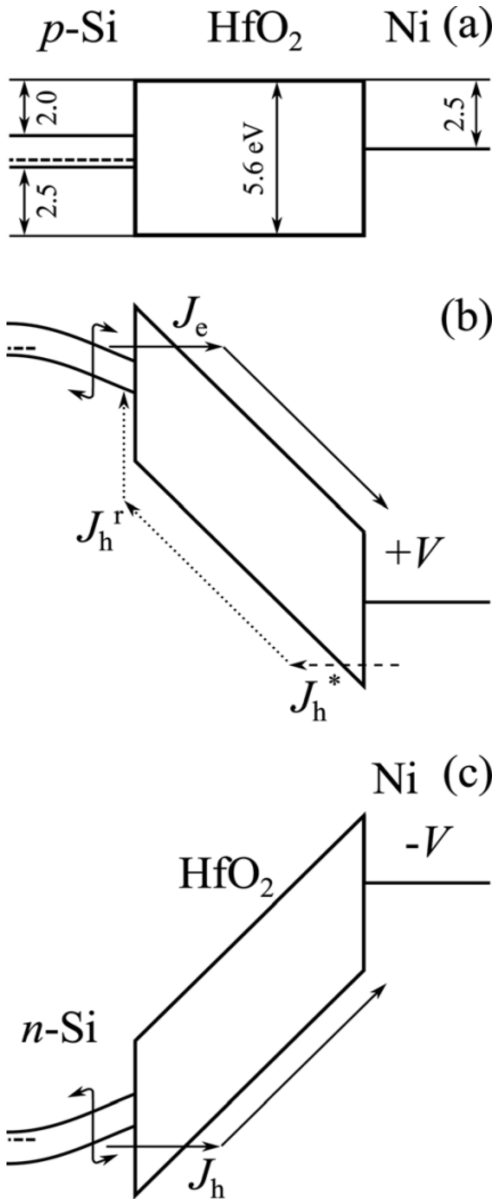
Two band conduction in HfO_2

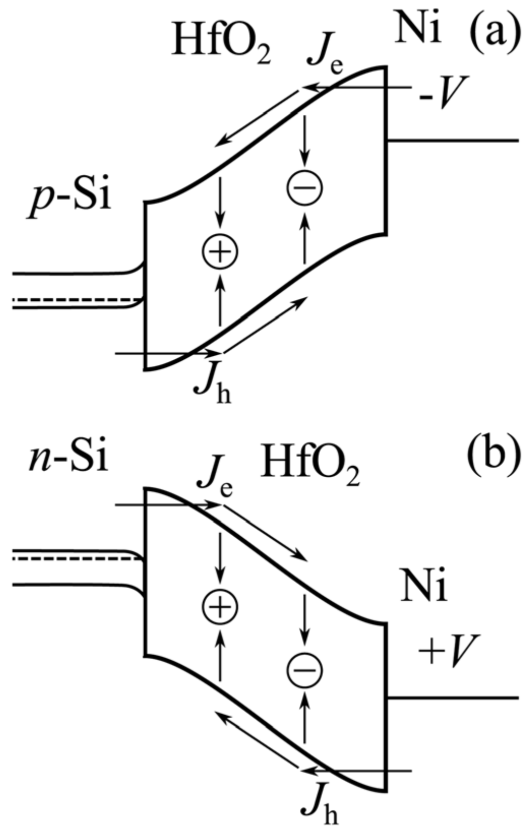




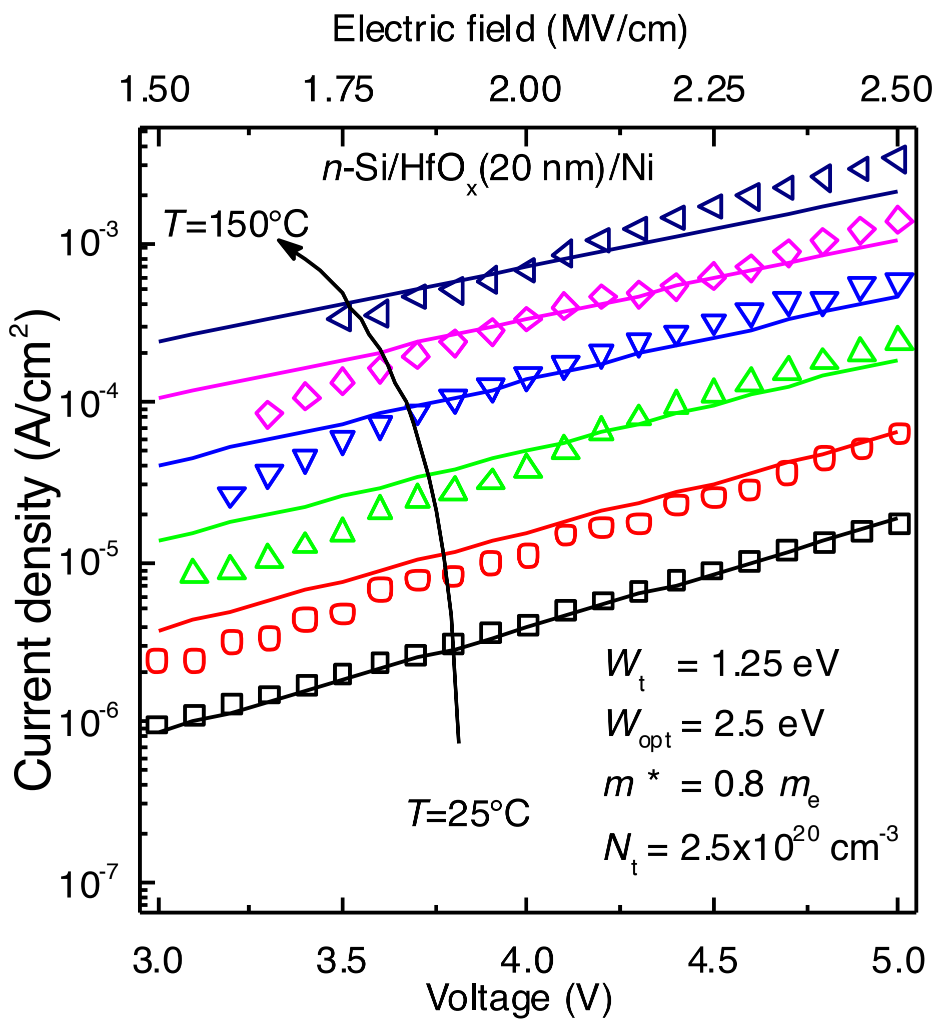
D.R. Islamov, V.A. Gritsenko, Appl. Phys. Lett. V99, p.672109, 2011

Two band conduction of HfO_2



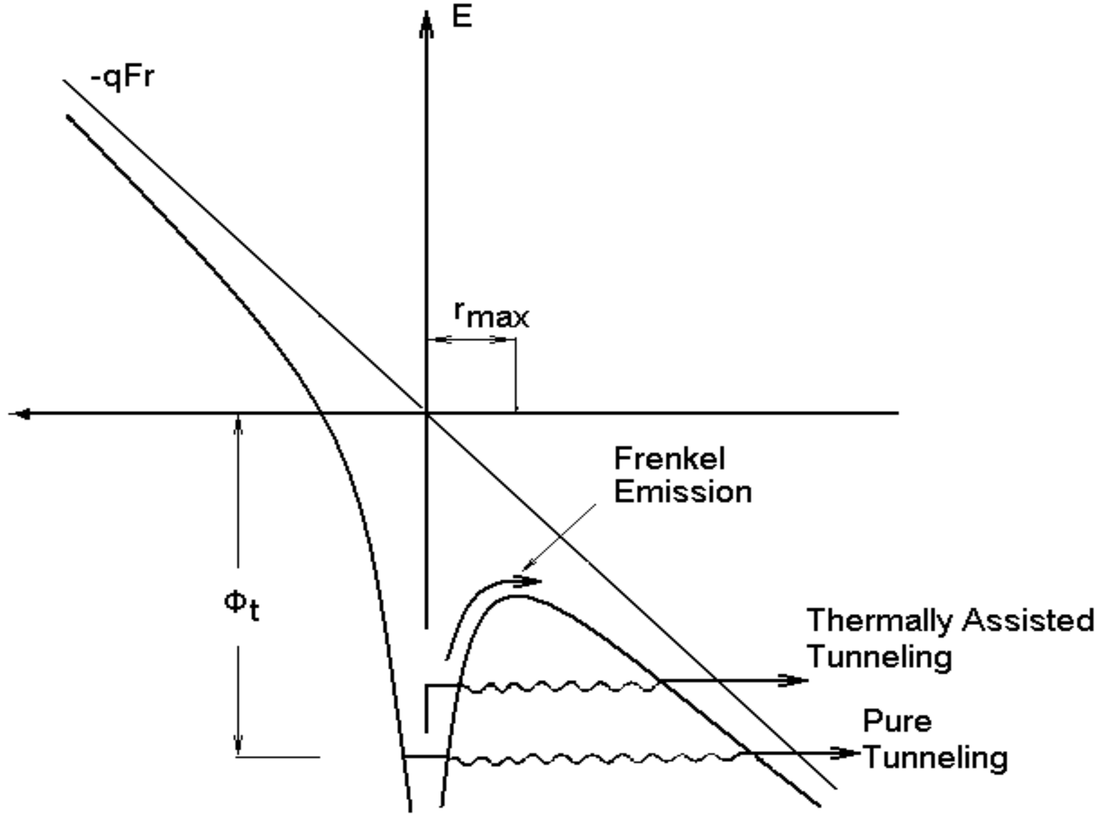


Charge transport in HfO_2



D.R. Islamov, V. A. Gritsenko, C. H. Cheng , A. Chin,
Origin of traps and charge transport mechanism in hafnia,
Appl. Phys. Lett. v.105, p.222901, 2014

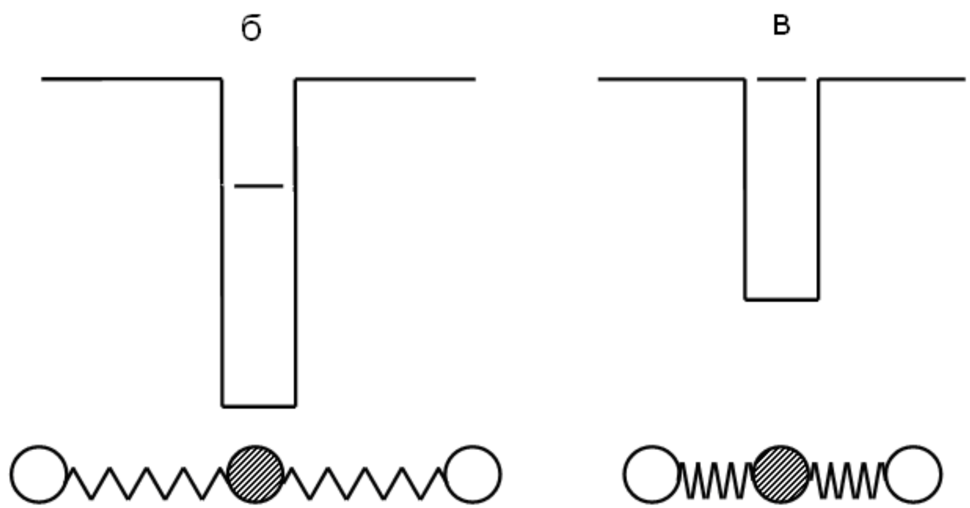
Frenkel effect



Frenkel model of coulomb trap

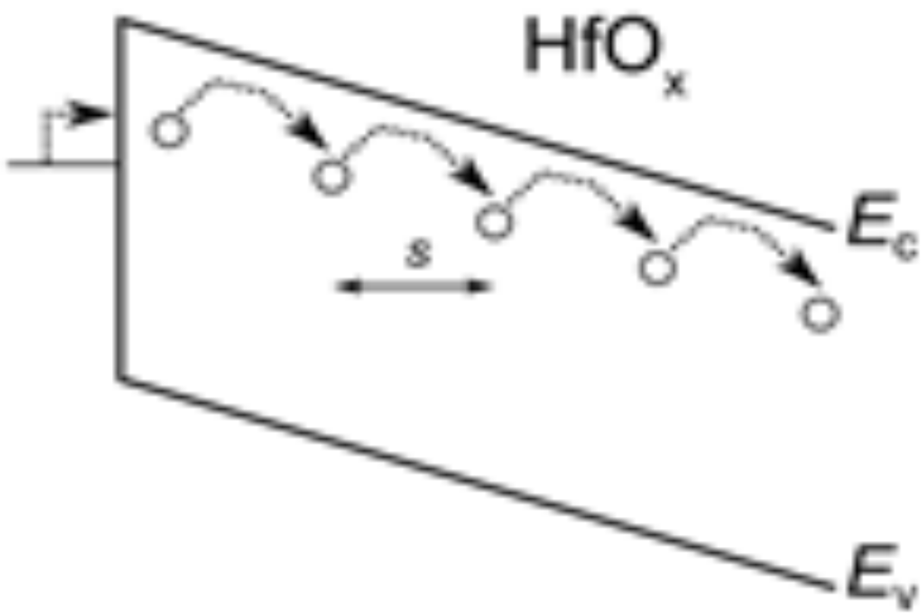
J. Frenkel, Phys. Rev. **54**, 647, 1938

Multiphonon trap ionization



Phonon-assisted charge transport between neighbor traps

Phonon-assisted tunneling between traps



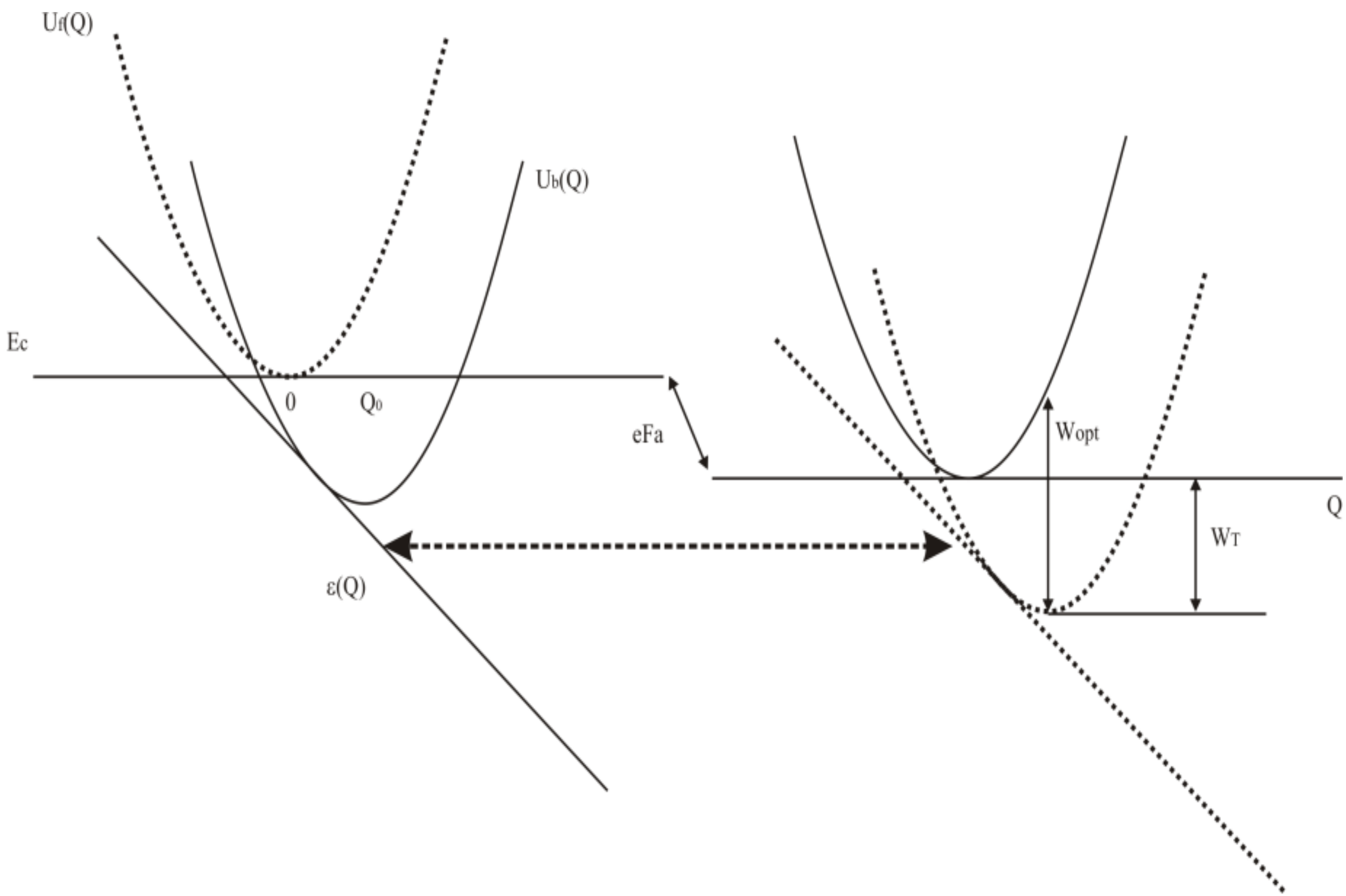
K.A. Nasyrov, V.A. Gritsenko, J. Appl. Phys. v.109, 093705, 2011.

Phonon-assisted charge transport

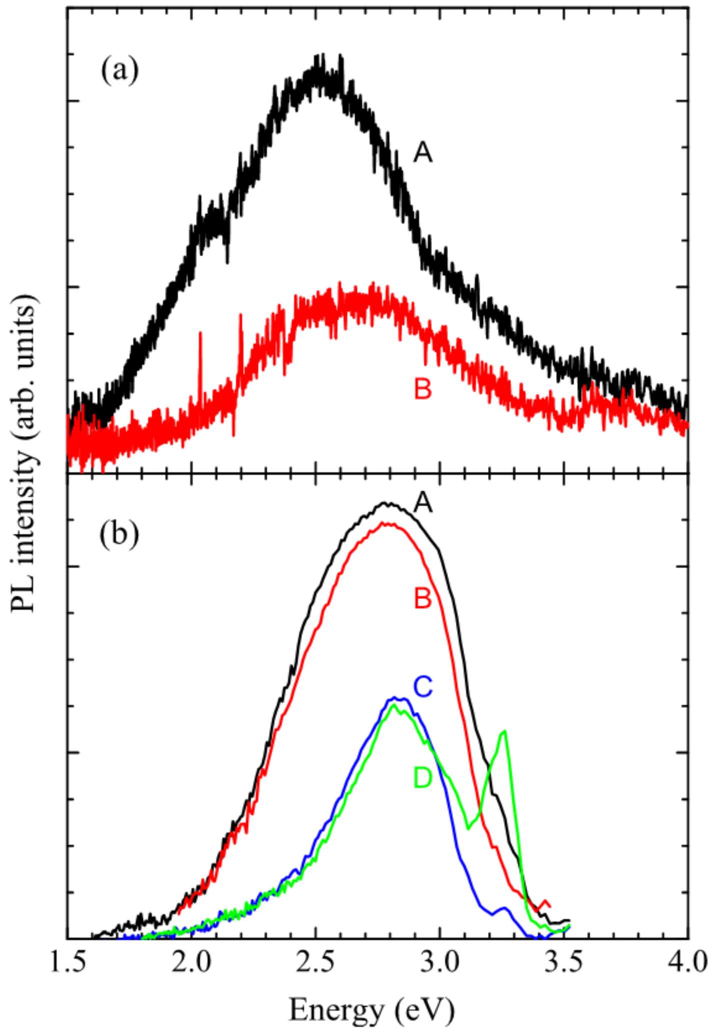
$$J = eN^{2/3}P, \quad P = \frac{2\sqrt{\pi}\hbar W_t}{m^* s^2 \sqrt{2(W_{opt} - W_t)}} \exp\left(-\frac{W_{opt} - W_t}{2kT}\right) \exp\left(-\frac{2s\sqrt{m^* W_t}}{\hbar}\right) \sinh\left(\frac{eFs}{2kT}\right)$$

where J – current density, e – electron charge, P – probability of electron tunneling between traps per second, W_t – trap thermal excitation energy, W_{opt} – of trap optical excitation energy, $s = N^{-1/3}$ – distance between traps, N-trap concentration, k – the Boltzmann constant, F – electric field.

Trap assisted charge transfer

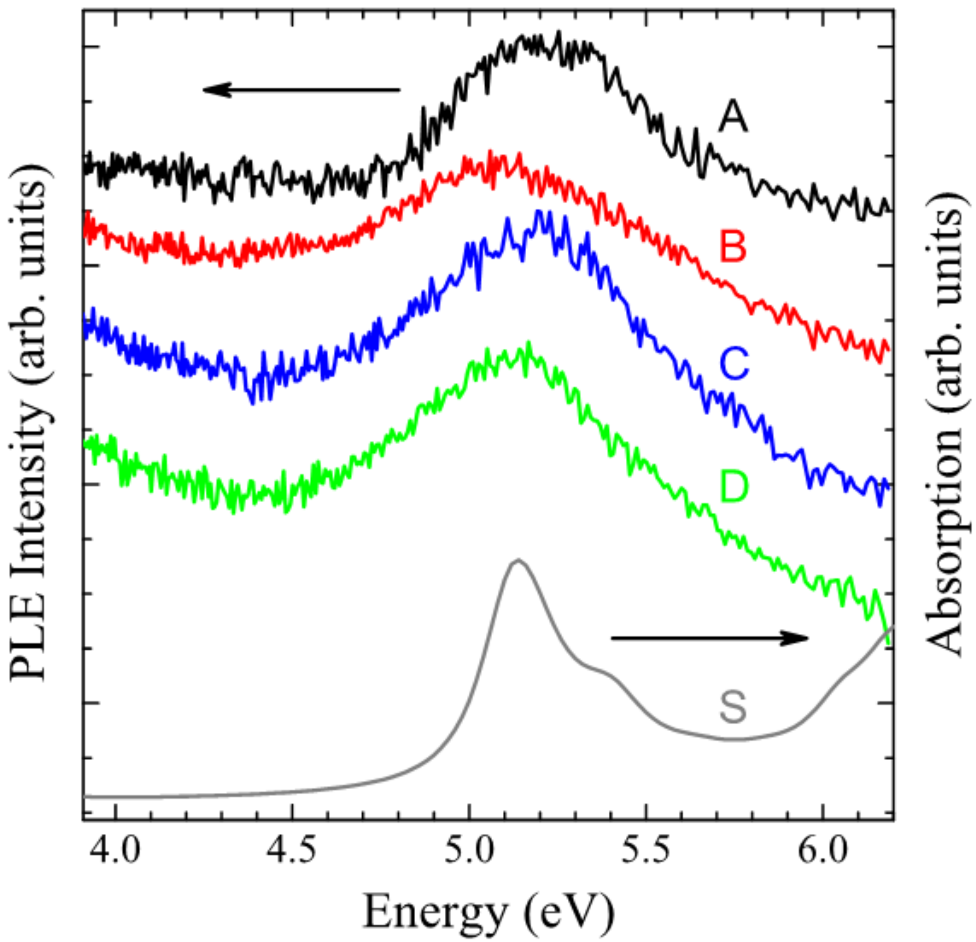


Blue (2.7 eV) photoluminescence band in ZrO_2

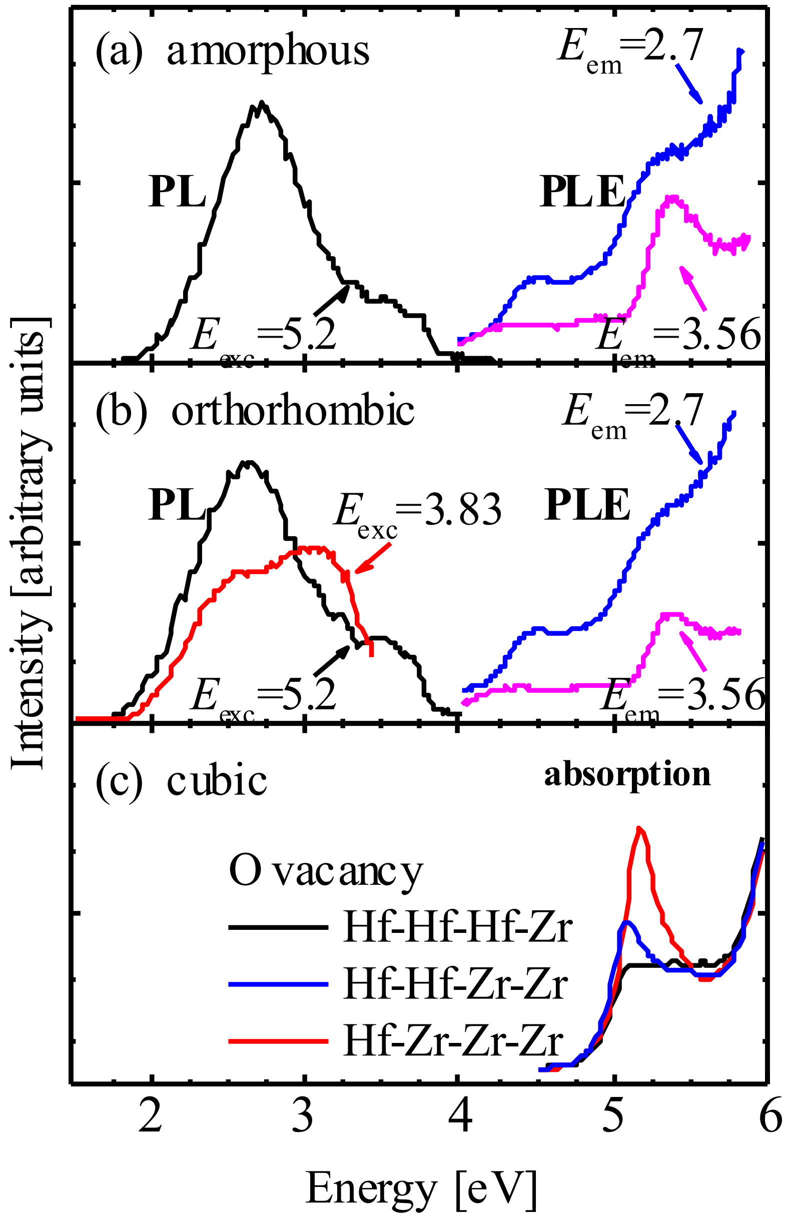


T.V. Perevalov, D.V. Gulyaev, V.S. Aliev, V.A. Gritsenko, The origin of 2.7 eV blue luminescence band in zirconium oxide, J. Appl. Phys. v.116, p.244109, 2014.

Photoluminescence excitation of 2.7 PL band in ZrO_2

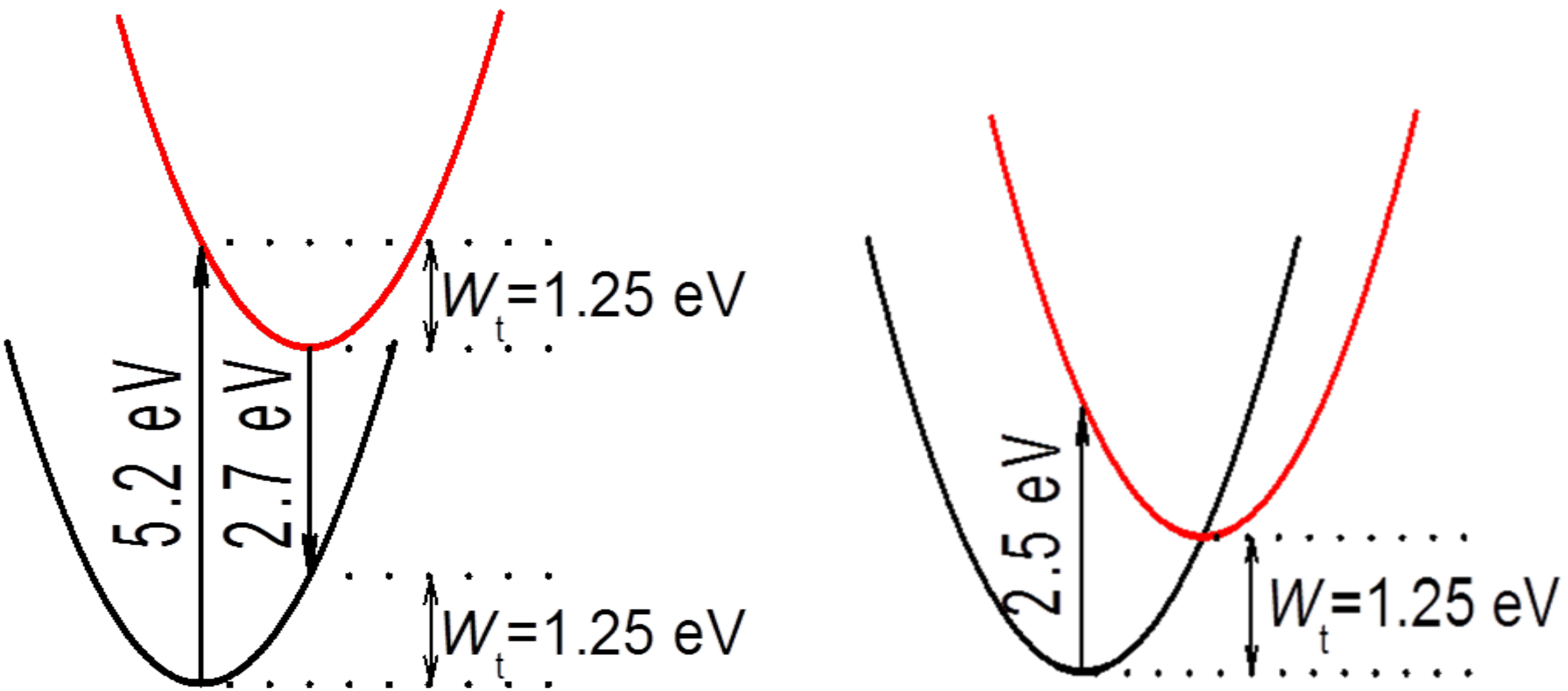


Photoluminescence in $Hf_{0.5}Zr_{0.5}O_2$



D. R.Islamov, T. V.Perevalov,
V. A.Gritsenko et. al.,
Charge transport in amorphous $Hf_{0.5}Zr_{0.5}O_2$,
Appl. Phys. Lett. v.106, p.102906, 2015.

Configuration diagram of oxygen vacancy and trap in HfO_2, ZrO_2 and $Hf_{0.5}Zr_{0.5}O_2$



Conclusion

- The memory effect in silicon nitride of TANOS is related to excess silicon, Si-Si bonds or Si clusters
- The defects responsible for the luminescence of amorphous Al_2O_3, HfO_2, ZrO_2, $Hf_{0.5}Zr_{0.5}O_2$ are oxygen vacancies
- The electron and hole traps responsible for the charge transport in amorphous Al_2O_3, HfO_2, ZrO_2, $Hf_{0.5}Zr_{0.5}O_2$ are oxygen vacancies

Thank You!