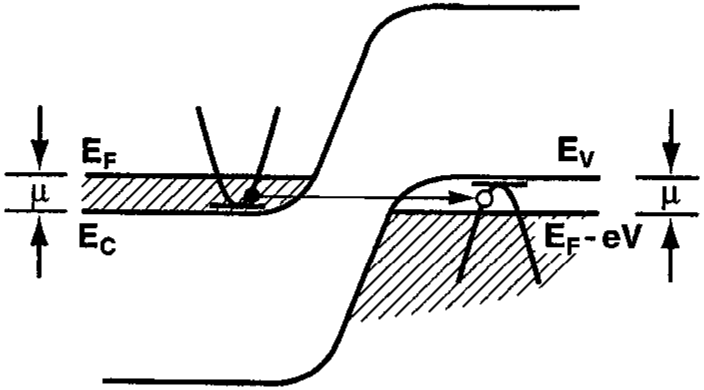
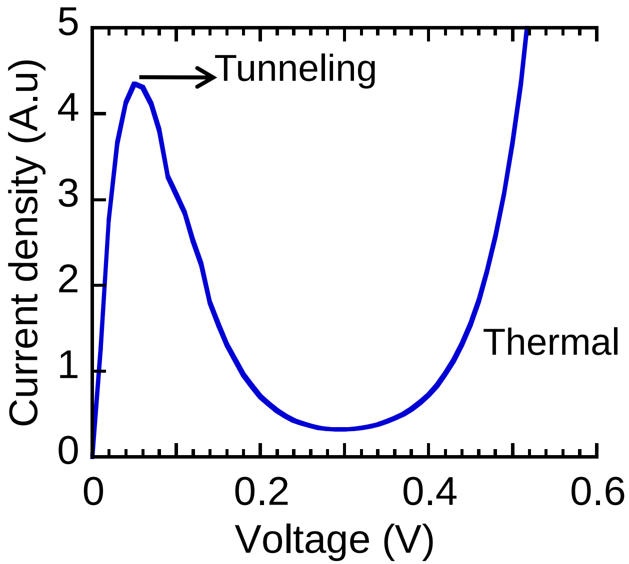
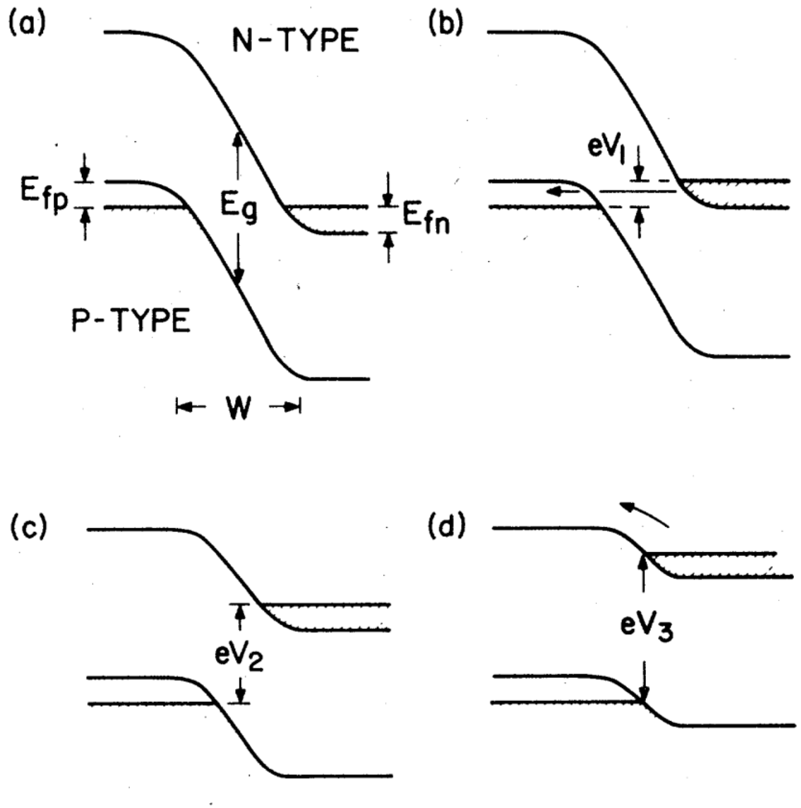
Tunneling in III-V Nitrides

Jai Verma, Kamal Karda and Satyaki Ganguly

Inter-band Tunneling

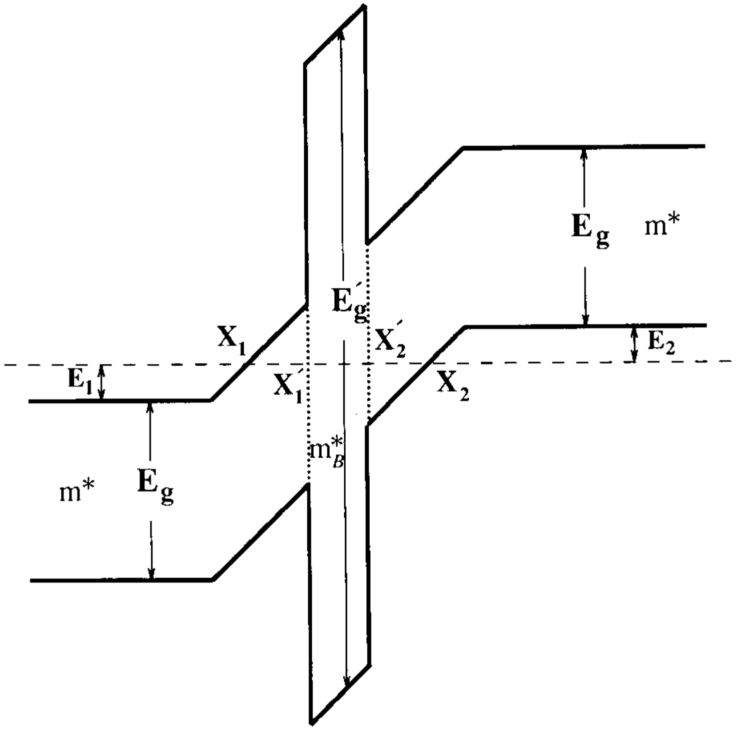




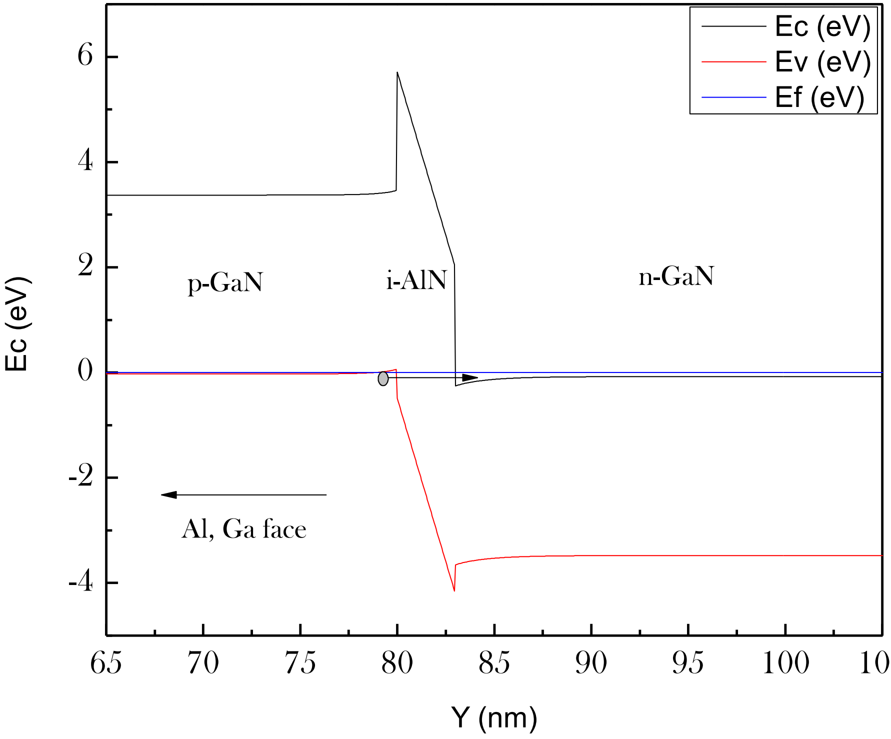


Ref: Esaki ,Rev. Mod. Phys, 1974

III-Nitrides for NDR and Zener Tunneling?



Yang et al; IEEE Tran Elec Dev, 1991



F=12MV/cm

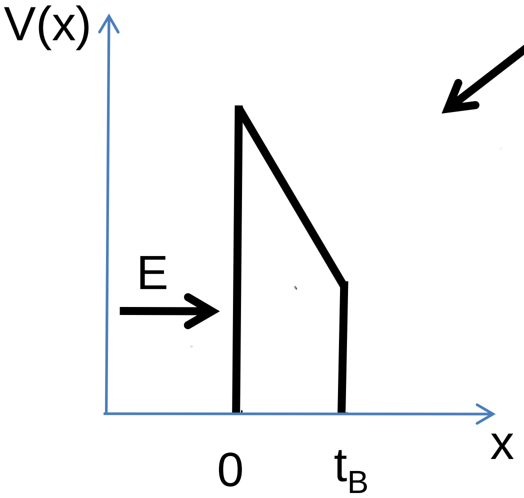
Formalism

$$J(E) = \mathit{injected\ flux} * \mathit{Twkb} * \mathit{available\ states}$$

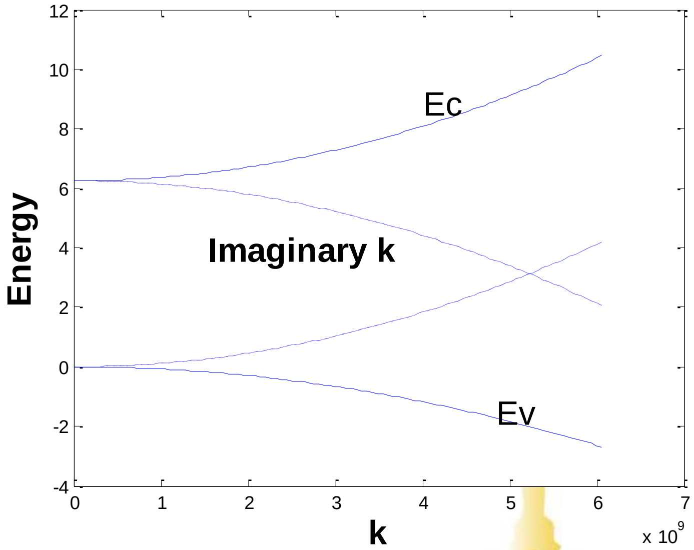
$$T_{wkb} = \exp\left(-2 * \int_0^{tbarrier} \mathrm{magk}(x)\,dx\right)$$

$$\mathrm{k}(x) = ?$$

or

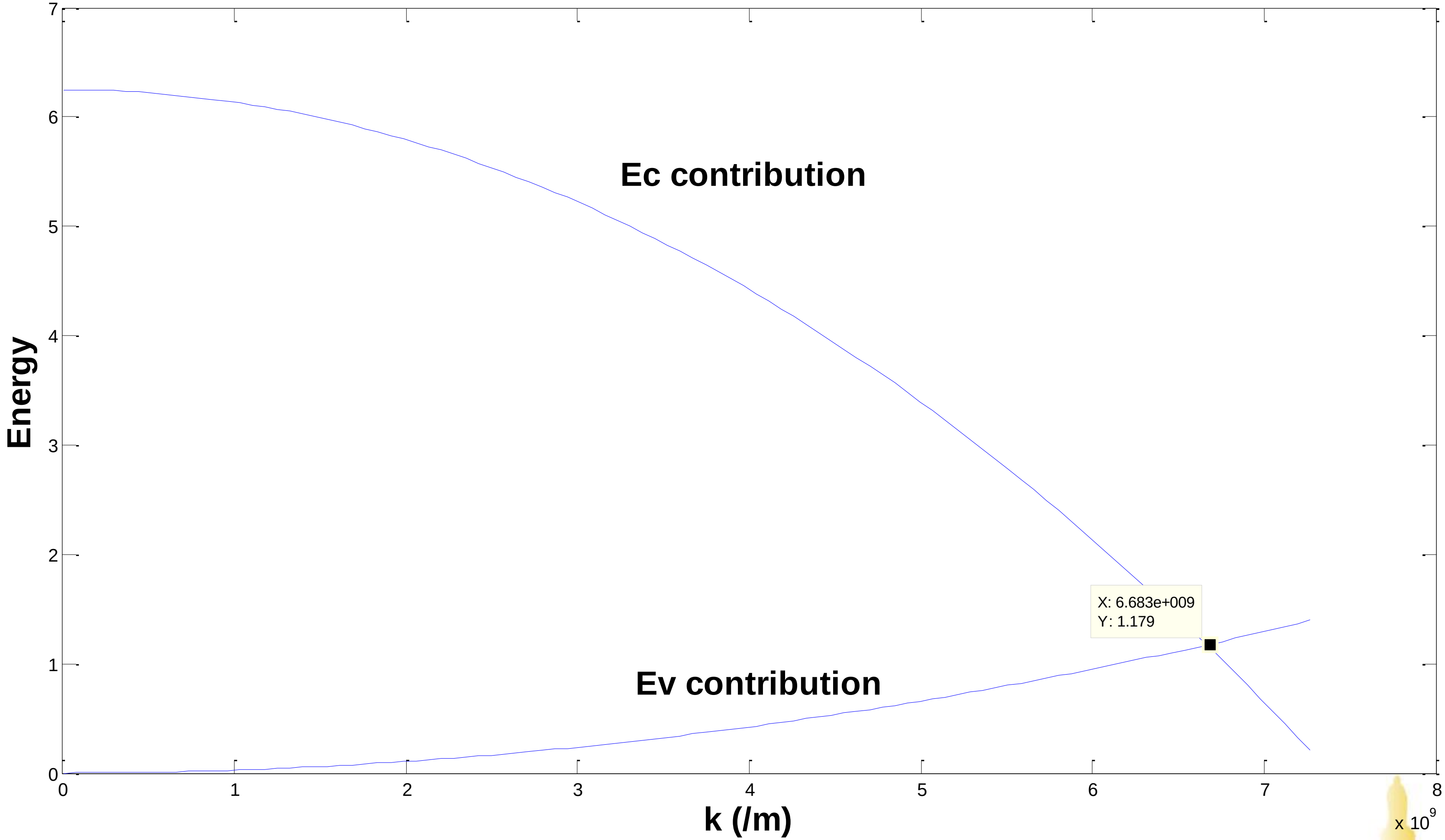


$$k(x) = \sqrt{\frac{2m^*(E - V(x))}{\hbar}}$$



Free electron model with fitted effective mass

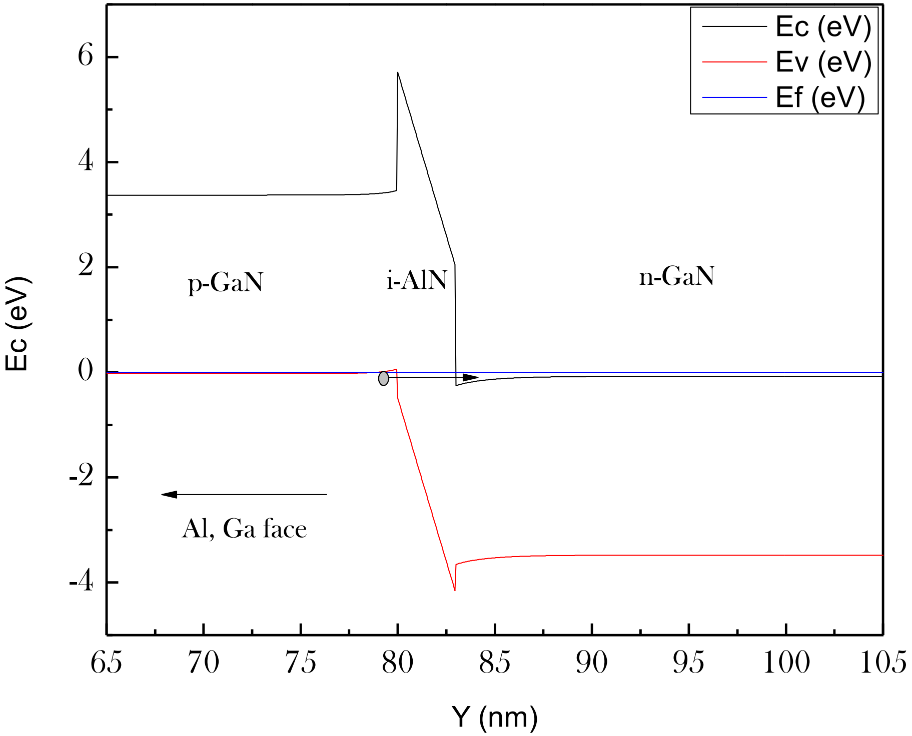
Imaginary E-K



mc=0.3; mhh [001] = 1.3;➔RINKE *et al* .PHYSICAL REVIEW B **77, 075202 2008**

Comparison

tAlN= 2.8nm



Potential approach:

T_{wkb} (E=0) = 4e-8

m fitted to experiment = 0.13 *m0*

Imaginary E-k approach:

T_{wkb} (E=0) = 3.9e-12

mhh[001] used for holes*

Device design

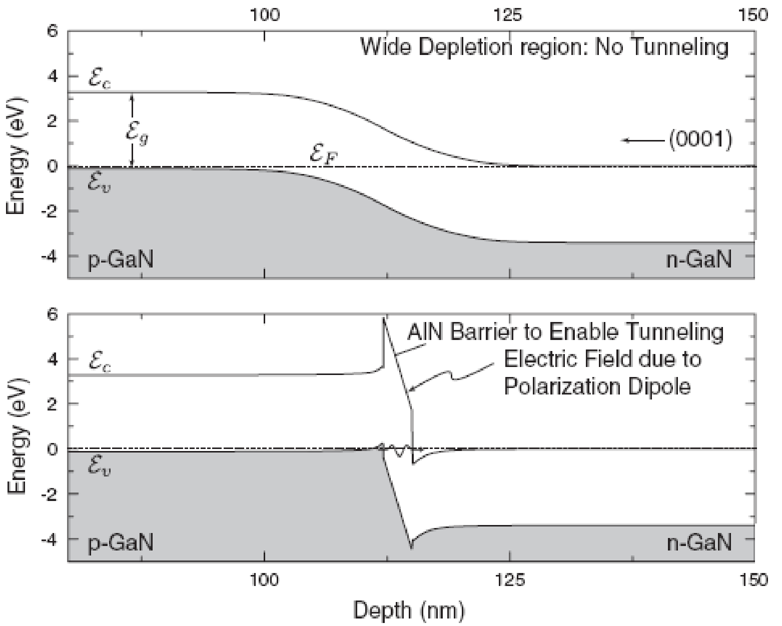
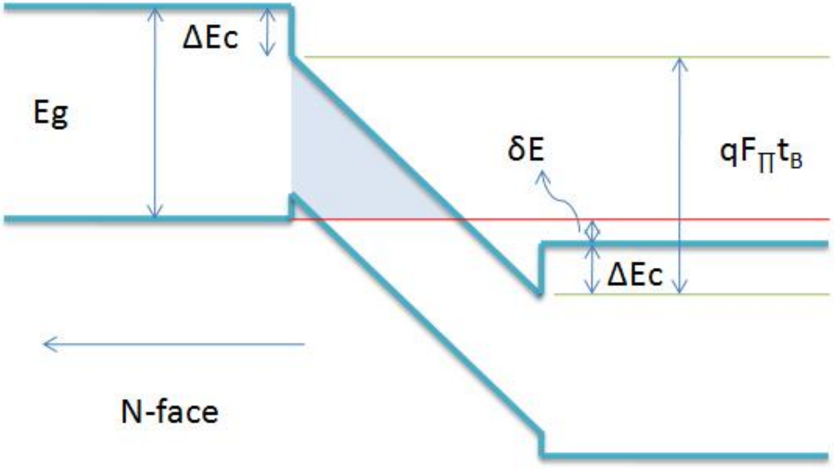


FIG. 1. Energy band diagrams of a normal *p*-*n* junction and a polarization-induced tunneling *p*-*n* junction. The polarization-induced electric field shrinks the depletion region and aligns the valence and conduction bands to facilitate interband tunneling.

J. Simon et al., PRL 103,026801 (2009)



$$Eg-\Delta Ec-qF_{\Pi}t_B+\Delta Ec+\delta E-qV=0$$

$$\Rightarrow \quad \delta E=qV-Eg+qF_{\Pi}t_B$$

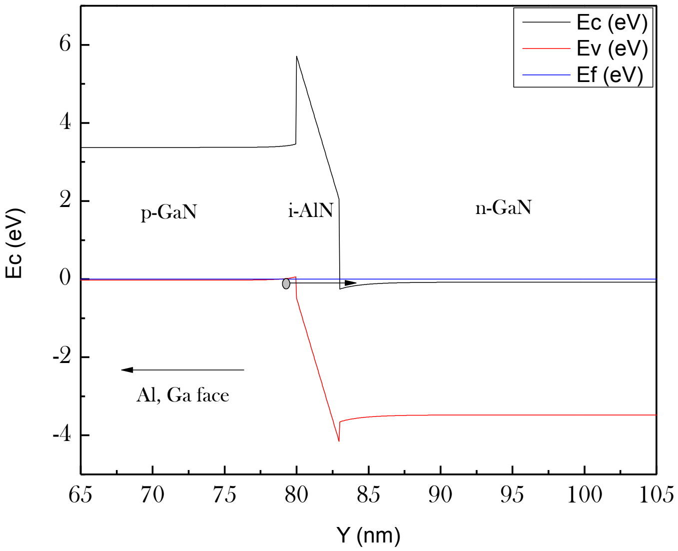
$\tau_{wkb} \approx e^{-2\int|\kappa(x)|dx}$ integrated over the tunnel barrier width t_B

where $K(x)=\sqrt{\frac{2m}{\hbar^2}(Eg-\Delta Ec+E-qF_{\Pi}x)}$

InGaN can give low barrier height to increase tunneling but has lower polarization field to reduce tunneling which effect dominates ?

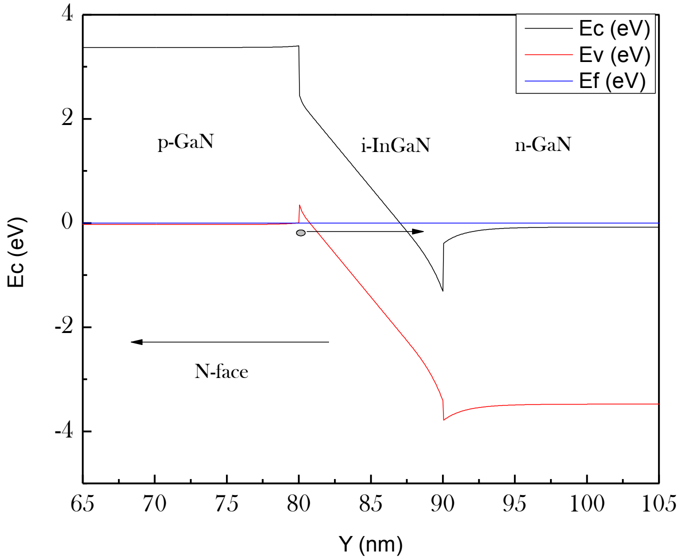
Also InGaN can be doped degenerately

Comparison



F≈12MV/cm

Tunnel diode on metal face with AlN as barrier

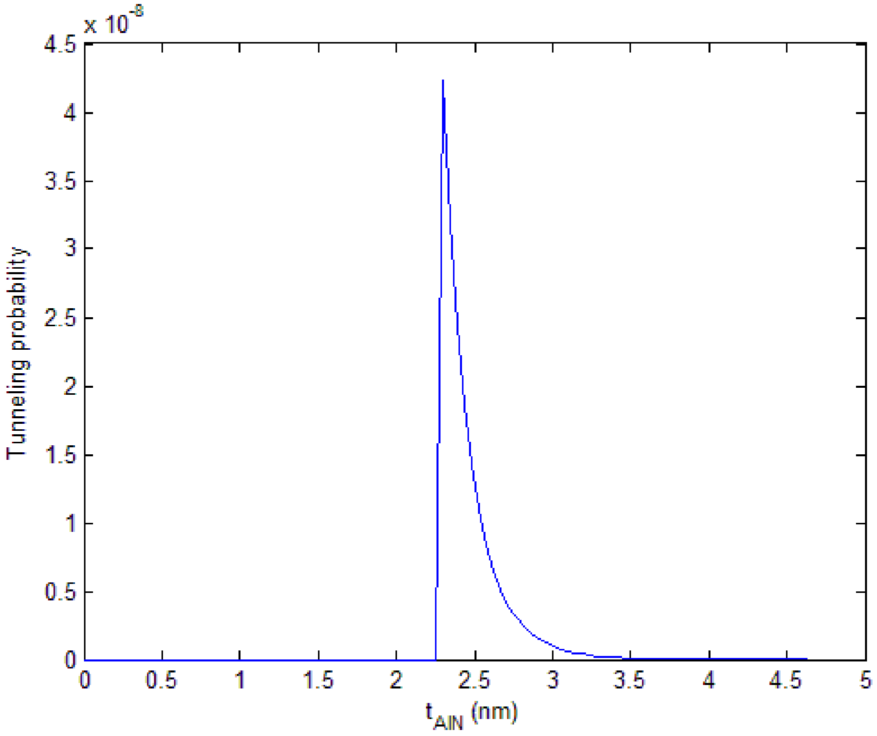


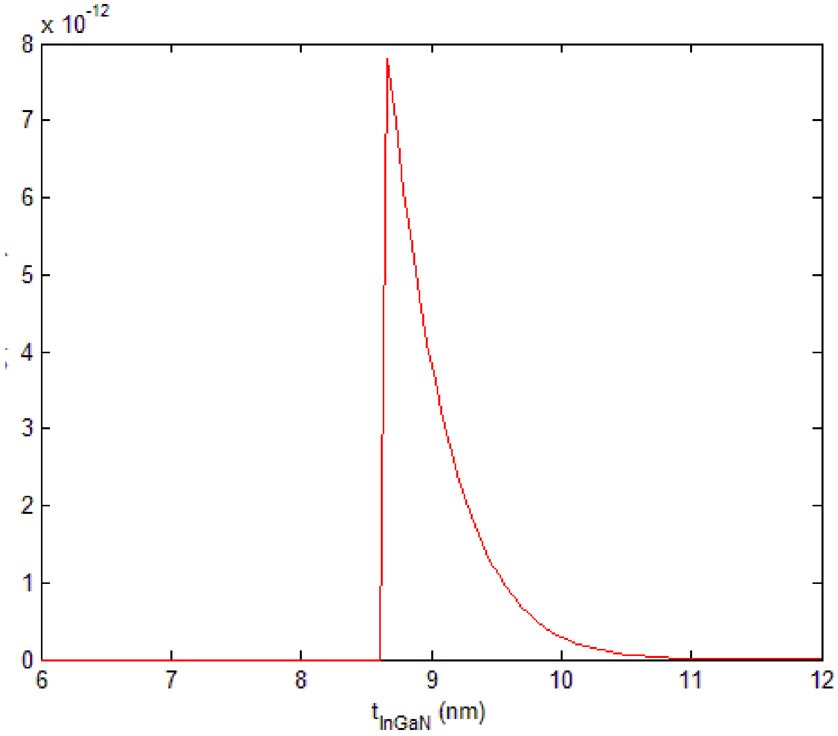
F≈3.5MV/cm

Tunnel diode on N- face with 50% InGaN as barrier

Tunneling probability curves with barrier thickness

Fitted effective mass approach



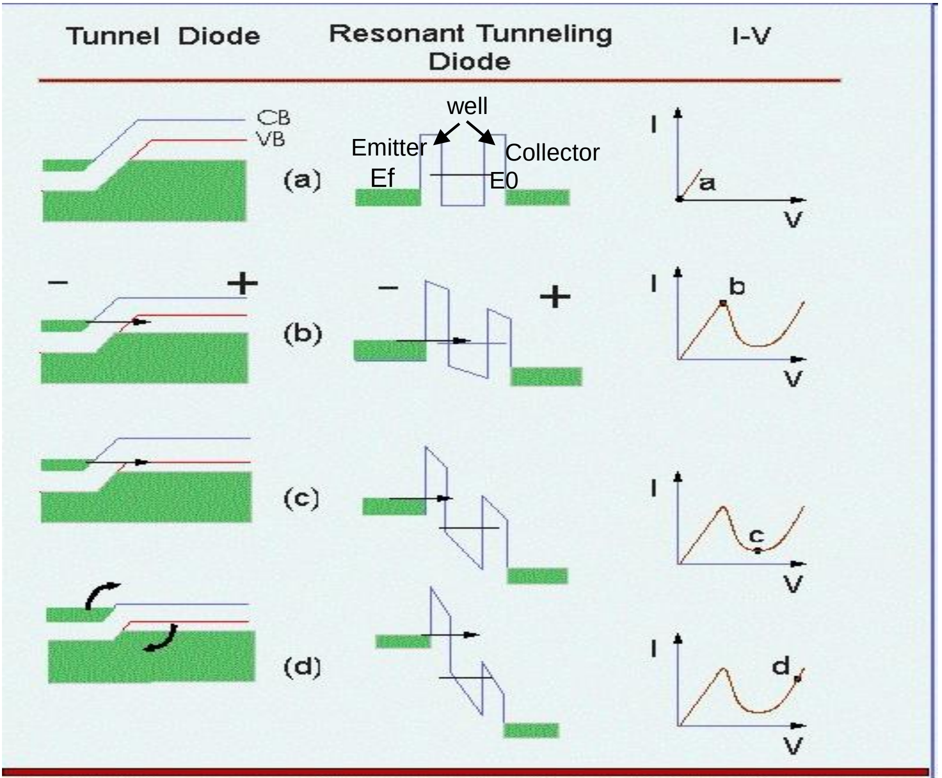


AlN as barrier

50% InGaN as barrier

The effective mass to be used for InGaN barrier needs to be ascertained

Resonant Tunneling Diode (overview)



A Double Barrier
Resonant Tunneling Structure

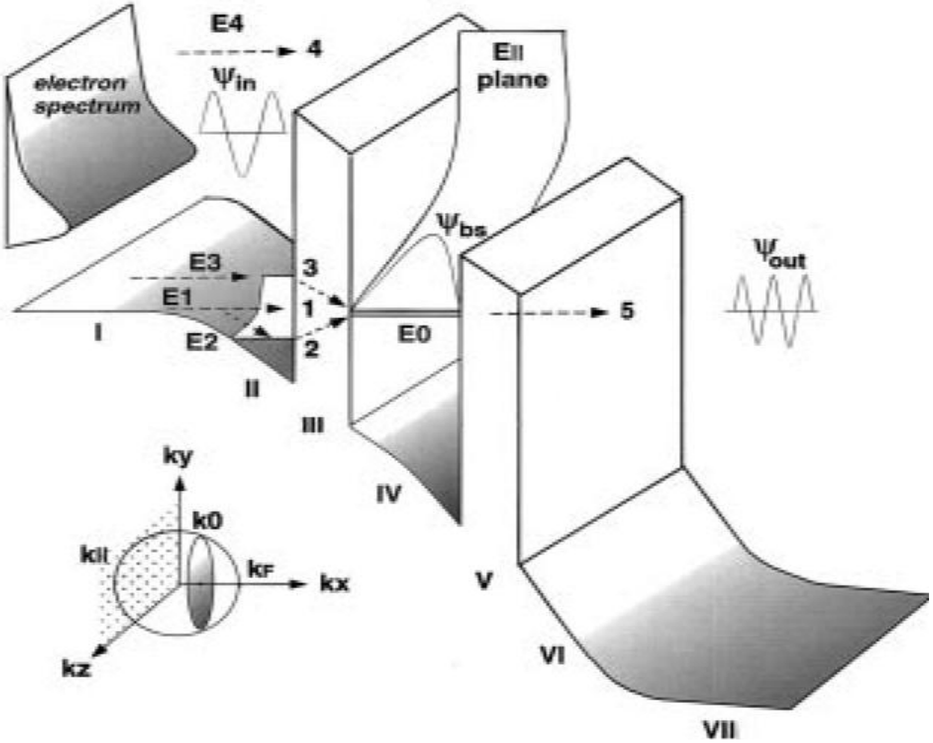
The idea was proposed by Kazarinov and Suris. (1971)

It shows NDR at RT and in Forward direction

It has got potential application in very high Speed/Functionality devices and circuits. Ultra fast operation upto THz order can be achieved

users.rcn.com/qsa/waveeng.html

RTD (Operating Principle)



Sun et al; IEEE Proceedings, 1998

- The electron energy in 3-D emitter can be written as:

$$E_{3D} = E_C + \frac{\hbar^2 k_x^2}{2m^*} + \frac{\hbar^2 k_\parallel^2}{2m^*}$$

- The electron energy in Quantum well is given by:

$$E_{2D} = E_n + \frac{\hbar^2 k_\parallel^2}{2m^*}$$

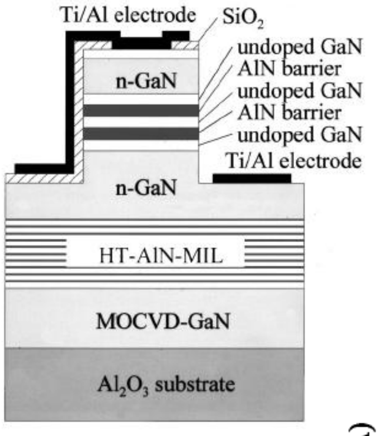
- As E_0 is accessible, tunneling is possible only for electrons with their momentum in a disk with $k_x = k_0$, in the emitter fermi sphere, where

$$k_0^2 = 2m^*(E_0 - E_C)/\hbar^2$$

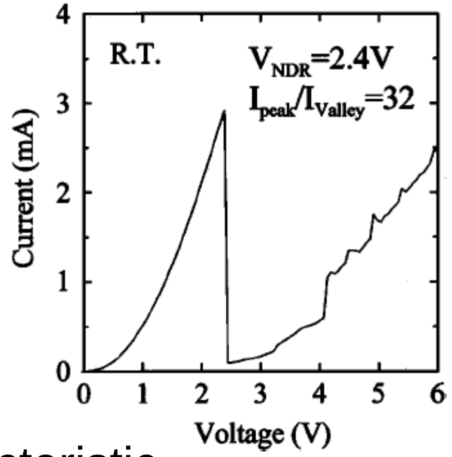
- For E0=Ec, it reaches max, then drops off. Further increase of bias will increase thermionic emission & tunneling through the top regions

RTD in Nitrides

- The high temperature, high power operation, high electron peak velocity makes nitride a compelling choice
- Relatively wide-range controllable band offset is promising for various quantum effect device application (eg:RTD)
- AlN/GaN double barrier RTD has been reported by kikuchi group. Peak to valley current ratio of ***32*** was reported



structure

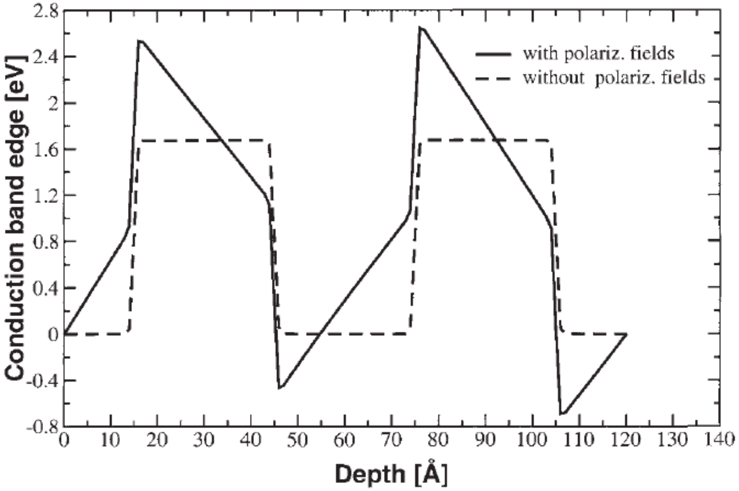


I-V characteristic

A. Kikuchi et al; APL, 2002

Polarization matching in Nitrides

- It is possible to design a quaternary heterostructure ($Al_xIn_yGa_{1-x-y}N$) which is polarization-matched and still exhibits a band gap large enough to result in a significant conduction band offset at the barrier interface.
- It has already been demonstrated that GaInN/AlGaInN LEDs show reduced efficiency droop, and improved output power.
- We want to investigate if there is any advantage of RTD structure with polarization matched materials.
- Let us first find out the polarization matched contours for nitrides.



F. Sacconi et al; PSS, 2002

$$J = \frac{e m^* k T \Gamma}{4\pi^2\hbar^3} \ln\left[\frac{1 + e^{(E_F - E_r + eV/2)/kT}}{1 + e^{(E_F - E_r - eV/2)/kT}}\right] \cdot \left[\frac{\pi}{2} + \tan^{-1}\left(\frac{E_r - \frac{eV}{2}}{\frac{\Gamma}{2}}\right)\right].$$

Polarization matching in Nitrides

- The bowing parameters are obtained from the literature shown in the table beside
- Using vegard's law the expression for spontaneous & total piezoelectric polarization is obtained shown below

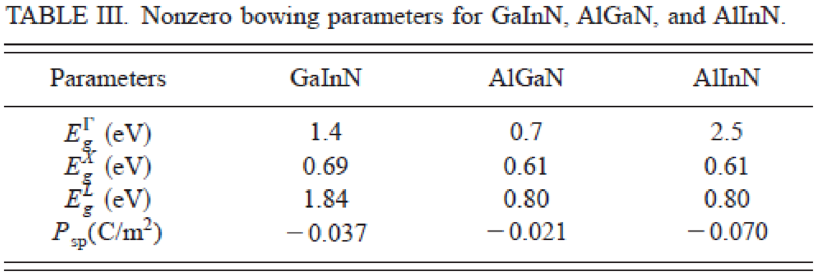


TABLE III. Nonzero bowing parameters for GaInN, AlGaN, and AlInN.

Parameters	GaInN	AlGaN	AlInN
E_g^{Γ} (eV)	1.4	0.7	2.5
E_g^{X} (eV)	0.69	0.61	0.61
E_g^{L} (eV)	1.84	0.80	0.80
P_{sp}(C/m^2)	-0.037	-0.021	-0.070

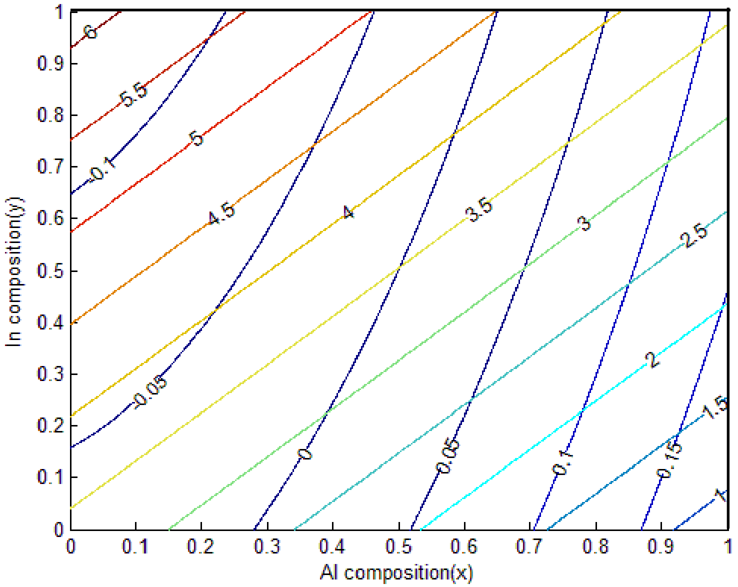
Vurgaftman et al; JAP, 2003

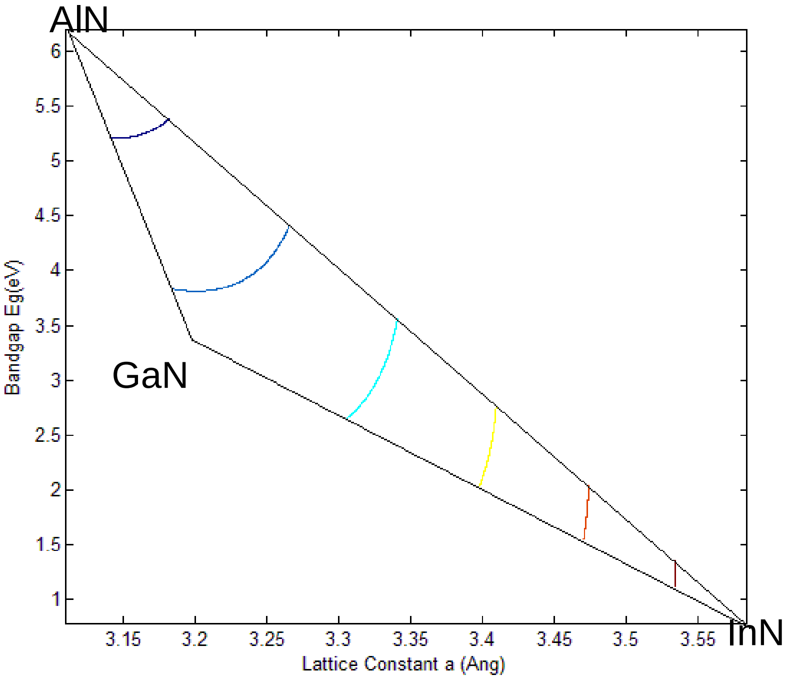
$$P_{sp}(Al_xIn_yGa_{1-x-y}N) = xP_{sp}(AlN) + yP_{sp}(InN) + (1-x-y)P_{sp}(GaN) + b_{AlGaN}x(1-x-y) + b_{InGaN}y(1-x-y) + b_{AlInN}xy + b_{AlInGaN}xy(1-x-y)$$

$$P_{pz}(Al_xIn_yGa_{1-x-y}N,\eta 1) = xP_{pz}(AlN,\eta 1) + yP_{pz}(InN,\eta 1) + (1-x-y)P_{pz}(GaN)$$

$$\eta 1(Al_xIn_yGa_{1-x-y}N) = \frac{[x(a^{GaN} - a^{AlN}) + y(a^{GaN} - a^{InN})]}{[x(a^{AlN} - ya^{InN}) + (1-x-y)a^{GaN}]}$$

Polarization matching in Nitrides





(blue line) Ga face polarization charge (c/m^2)
And band gap (color lines, in eV) contours of quaternary
AlxInGaN grown Pseudomorphically on GaN substrates

Bandgap vs lattice constant, contour plot

So with 2 degrees of freedom, we can have polarization matched structure with desired B.G!

Ongoing work

- Quantitative values of NDR curve.
- Comparison of currents with potential representation approach and imaginary E-k approach for AlN and InGaN barrier.
- Current-voltage characteristics of Polarization compensated resonant tunneling structure.
- Explore a suitable quaternary material to get high polarization field and lower bandgap for high tunneling currents.
- This work explores the application of III-V Nitrides for NDR devices useful for memories.