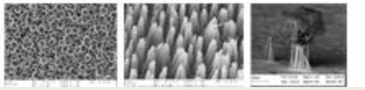
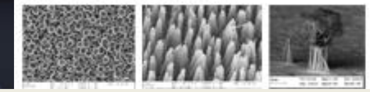


Modelling of the Coulombic centres charge emission: electric field approximation comparison in simulating the measured TSC signal

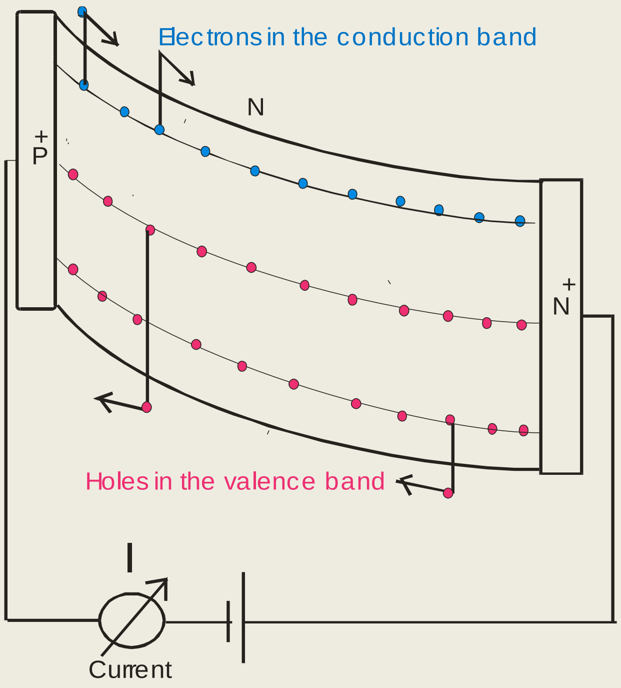
Lucian D. Filip and Ioana Pintilie
National Institute of Materials Physics, Bucharest, Magurele, Romania

Outline

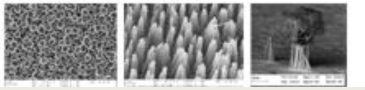
- Basic TSC introduction, standard approach (non-Coulombic defect centres)
- Coulombic centres (e.g. B_iO_i, H116K, H152K…)
  - General Poole-Frenkel theory
  - Electric field approximations
- Results and comparisons of different approaches
- Conclusions



TSC basics: standard approach



- ✓ The sample is cooled at low temperatures (10 K or below)
- ✓ Charge is injected into defect traps using an applied electrical field.
- ✓ A reverse bias larger than the depletion bias (such that the space charge region covers the entire volume) is applied (full depletion regime).
- ✓ The sample is heated with a constant heating rate and the emission current is measured.



TSC basics: standard approach

$$I_{TSC}(T) = \frac{q\,A\,d}{2}\, e_n(T)\, n_{traps}(T)$$

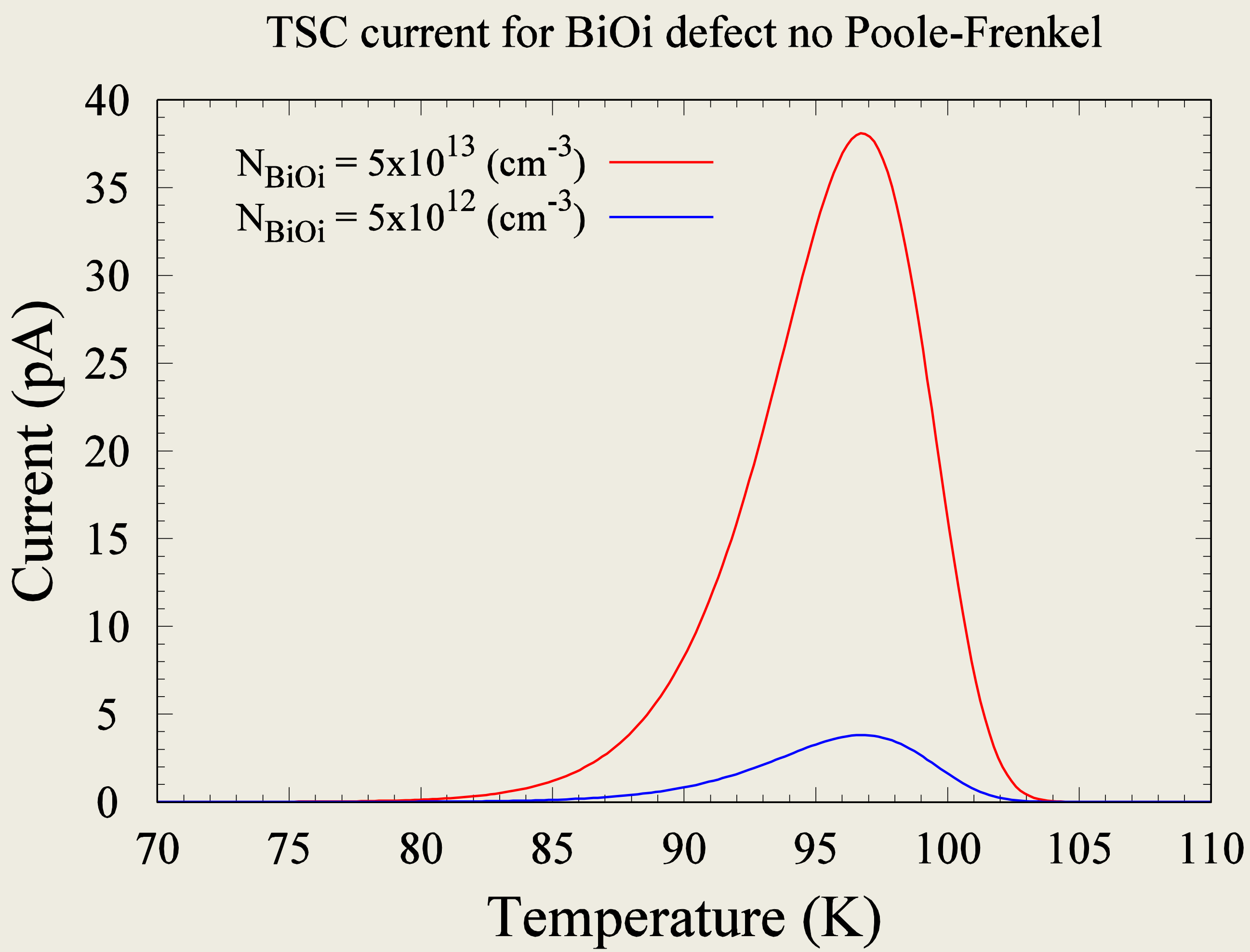
$$n_{traps}(T) = n_{traps}(T_0)\, exp\left(- \int\limits_{T_0}^{T} \frac{1}{\beta}\, e_n(T')dT' \right)$$

$e_n(T)$ - the emission rate for electrons with a constant activation energy (E_a) (not dependent on the electric field!)

$n_{traps}(T_0)$ - density of filled traps at T_0

- ✓ No charge recombination is considered in the active region

TSC basics: standard approach



$\sigma_n = 1.05x10^{-14}$ cm^2

$E_a = 0.25$ (eV)

TSC current: Coulombic centres

- $\mathbf{E_a \neq}$ **constant**! E_a is dependent on the electric field F(x) in the active region.
- $E^0_a(F=0) > E_a(F \neq 0)$

- *Poole- Frenkel emission mechanism* must be used

- F(x) as for an abrupt junction must be considered as well
- F(x) depend on the doping of the device (charge density)

$F(x)$
- Is essentially unknown
- Approximations must be used

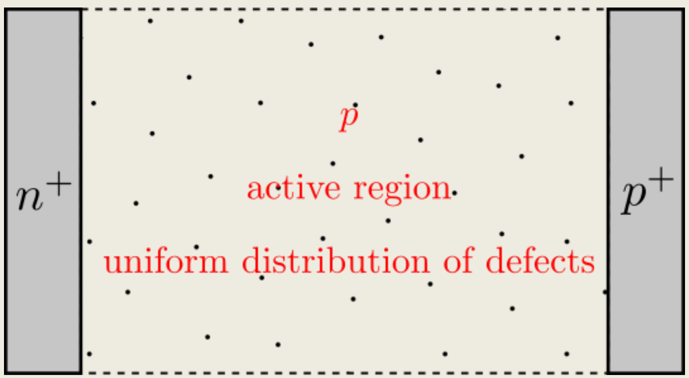
Which approach should be used?

National Institute of Materials Physics
Atomistilor Str. 105bis, PO Box MG7, Magurele, Bucharest, Romania, 077125,Telephone : +40213690185
Fax: +40213690177, E-mail : director@infim.ro, www.infim.ro

Results: electric field approximations

I. <u>Charge density at room temperature Na=[Bs]</u>

- Poisson equation is solved for the uniform effective charge density at room temperature.

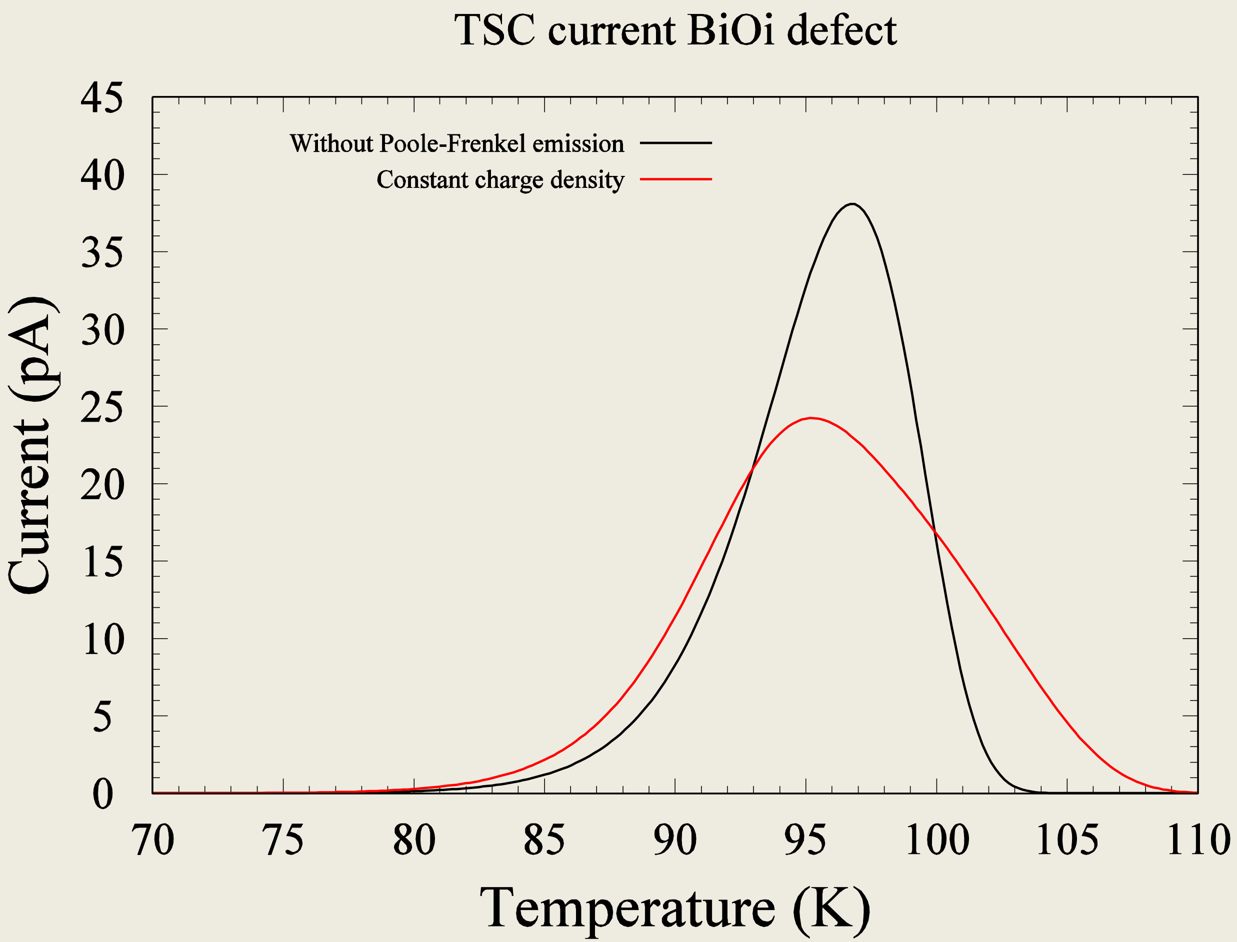


$$F(x) = \frac{q\,N_a}{\varepsilon}(d-x) + \frac{V - V_{depletion}}{d}$$

$$N_a = \text{Boron doping concentration } ([B_s])$$

Results: electric field approximations

$$F(x) = \frac{q\,N_a}{\varepsilon}\,(d - x) + \frac{V - V_{depletion}}{d}$$



$N_a = 1x10^{14}$ (cm^{-3})

$n_{BiOi} = 5x10^{13}$ (cm^{-3})

V = 190 (V)

$\sigma_n = 1.05x10^{-14}$ cm^2

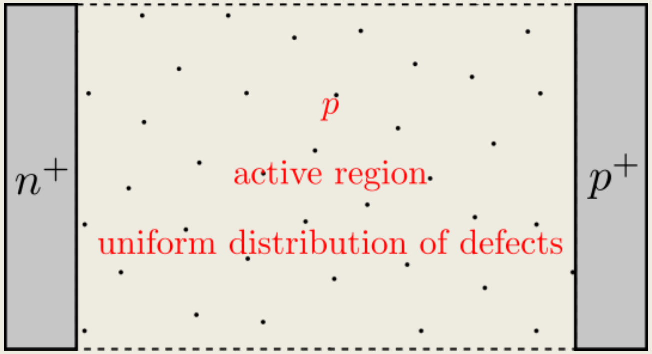
$E_a = 0.25$ (eV)

$E_a^0 = 0.28$ (eV)

Results: electric field approximations

II. Temperature dependent charge density

- Poisson equation is used to calculate the electric field for a uniform charge distribution.
- The field for the current temperature step is calculated using the charge density from the previous temperature step.



$$N_{eff}(T) = N_a - 2 \cdot N_{BiOi} + n_{BiOi}(T)$$

Results: electric field approximations

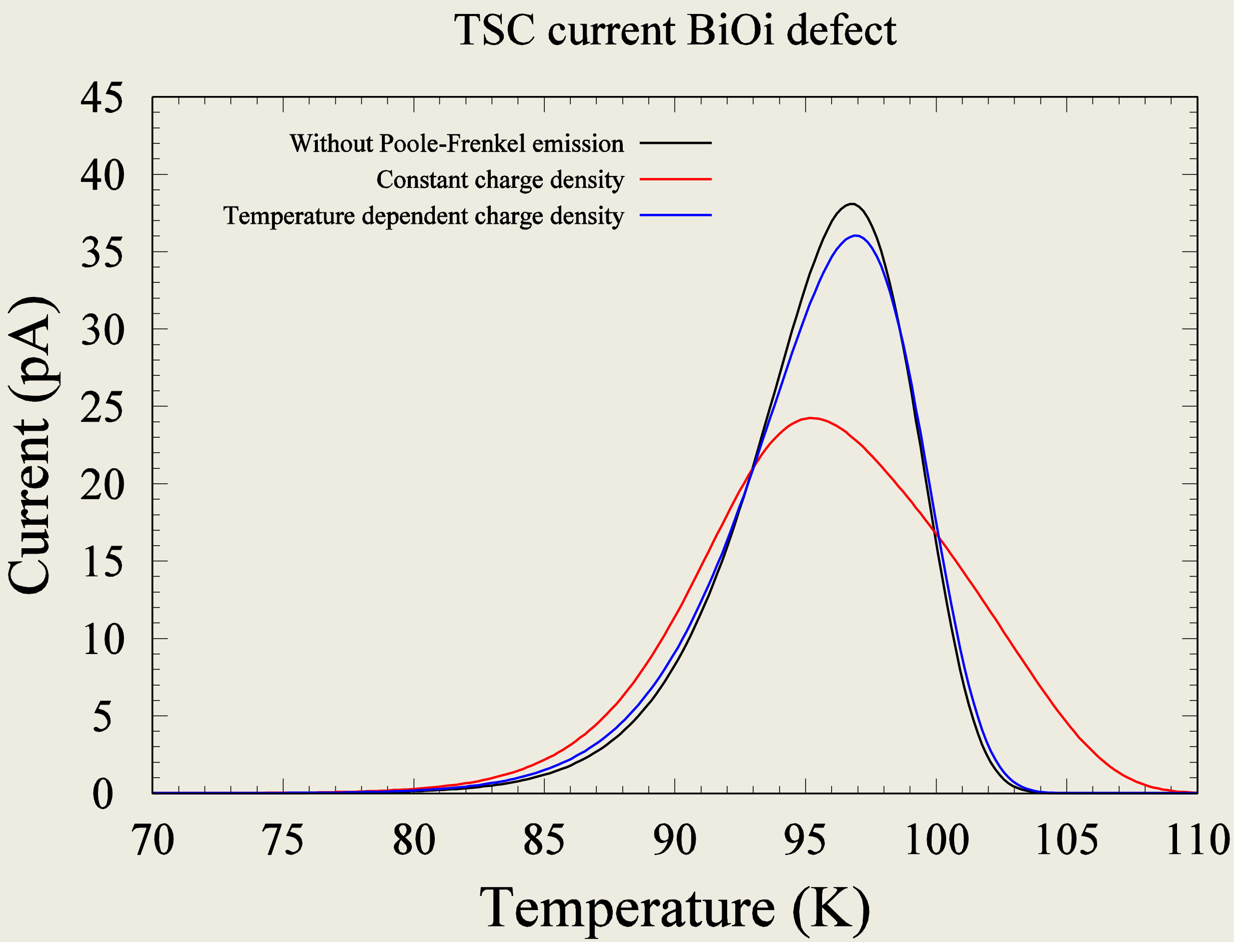
$$F(x,T) = \frac{q\,N_{eff}(T)}{\varepsilon}\,(d-x) + \frac{V - V_{depletion}(T)}{d}$$

Electron activation energy without an applied field!
(generally very difficult to obtain and impossible to measure!)

$$n_{BiOi}(T) = N_{BiOi}\,\frac{1}{d}\int_0^d exp\left[-\frac{1}{\beta}\int_{T_0}^{T} \sigma_n\,\nu_{th}(t)\,Nc(t)\,e^{-\frac{E_a^0}{k_B\,t}} \times \right.$$
$$\left. \times \left[\left(\frac{k_B\,t}{q}\sqrt{\frac{q\,F(x,T)}{\pi\,\varepsilon}}\right)^2 \left(e^{\frac{q}{k_B\,t}\sqrt{\frac{q\,F(x,T)}{\pi\,\varepsilon}}}\left(-1+\frac{q}{k_B\,t}\sqrt{\frac{q\,F(x,T)}{\pi\,\varepsilon}}\right)+1\right)+\frac{1}{2}\right] dt\right] dx$$

Results: electric field approximations

$$F(x,T) = \frac{q\,N_{eff}(T)}{\varepsilon}(d-x) + \frac{V - V_{depletion}(T)}{d}$$



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$n_{BiOi} = 5x10^{13}$ (cm^{-3})

V = 190 (V)

$\sigma_n = 1.05x10^{-14}$ cm^2

$E_a = 0.25$ (eV)

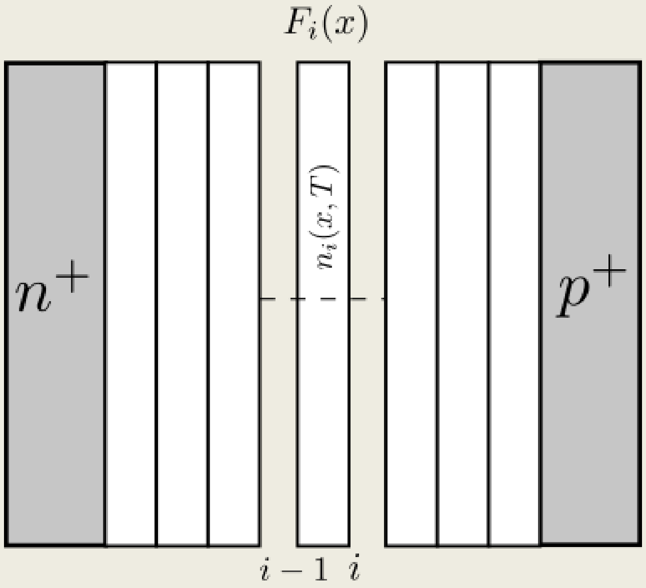
$E_a^0 = 0.28$ (eV)

Results: electric field approximations

III. Finite element approach

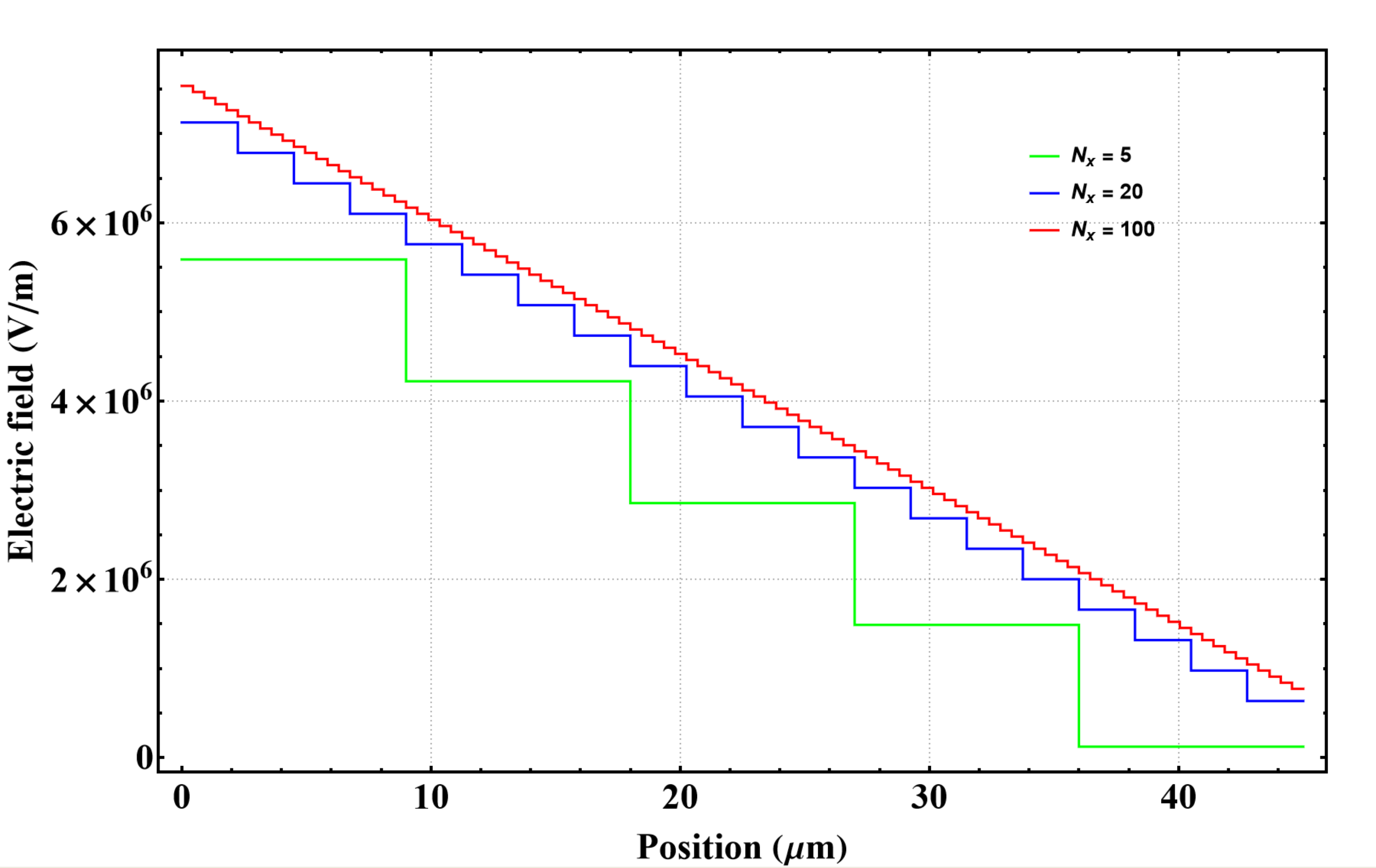
$$N_{eff}(T) = \frac{1}{N_x} \sum_{i=1}^{N_x} n_i(T)$$

- Active region is split in a number N_x of equal slices.
- The charge density is uniform in each slice at each temperature step.
- The electric field is calculated in each slice at each temperature step.
- Continuity conditions are imposed at the interfaces between neighbouring slices.
- No charge recombination is considered in the active region



$$F_i(x,T) = \frac{q}{\varepsilon} n_i(T) \left[(i-1)\frac{d}{N_x} - x \right] + \frac{q}{\varepsilon}\frac{d}{N_x} \sum_{k=i}^{N_x} n_k(T) + \frac{V - V_{depletion}(T)}{d}$$

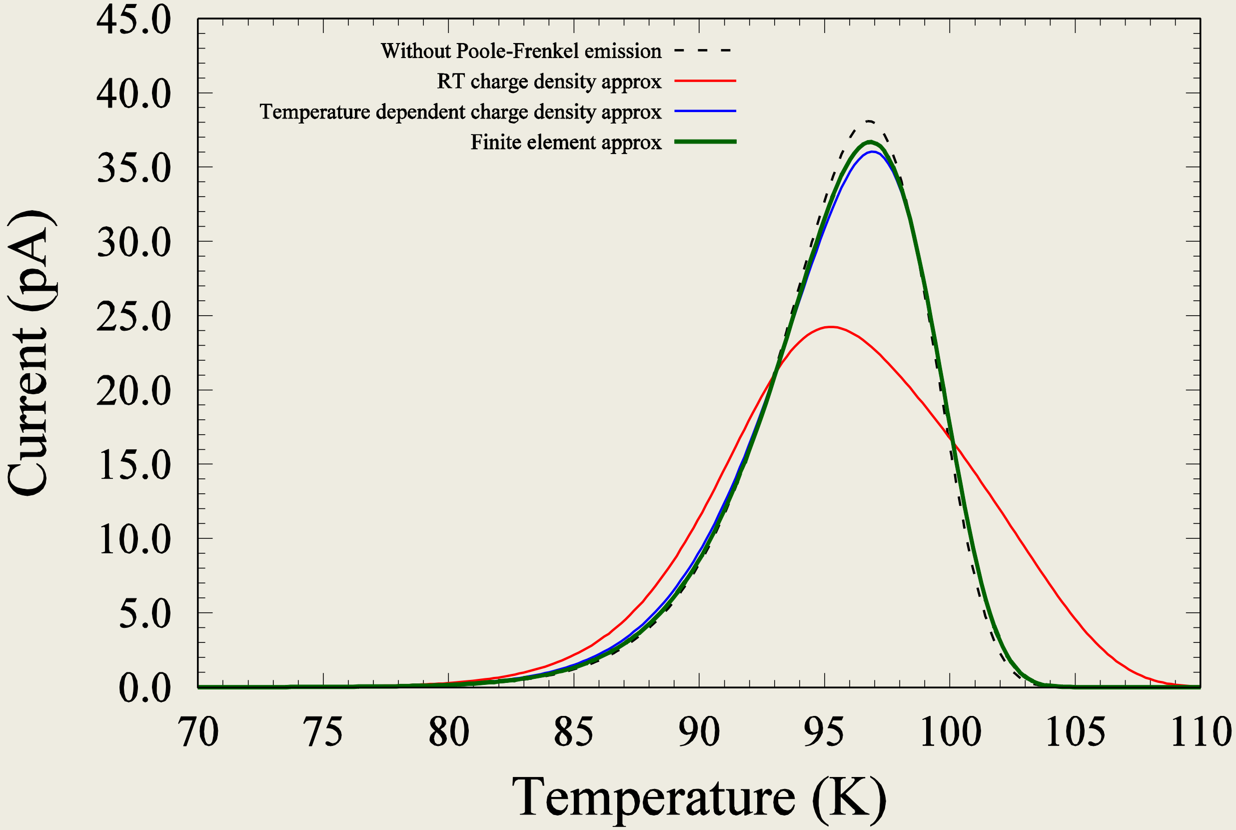
Results: electric field approximations



Results: electric field approximations

$$F_i(x,T) = \frac{q}{\varepsilon} n_i(T) \left[(i-1)\frac{d}{N_x} - x \right] + \frac{q}{\varepsilon}\frac{d}{N_x}\sum_{k=i}^{N_x} n_k(T) + \frac{V - V_{depletion}(T)}{d}$$

TSC current BiOi defect



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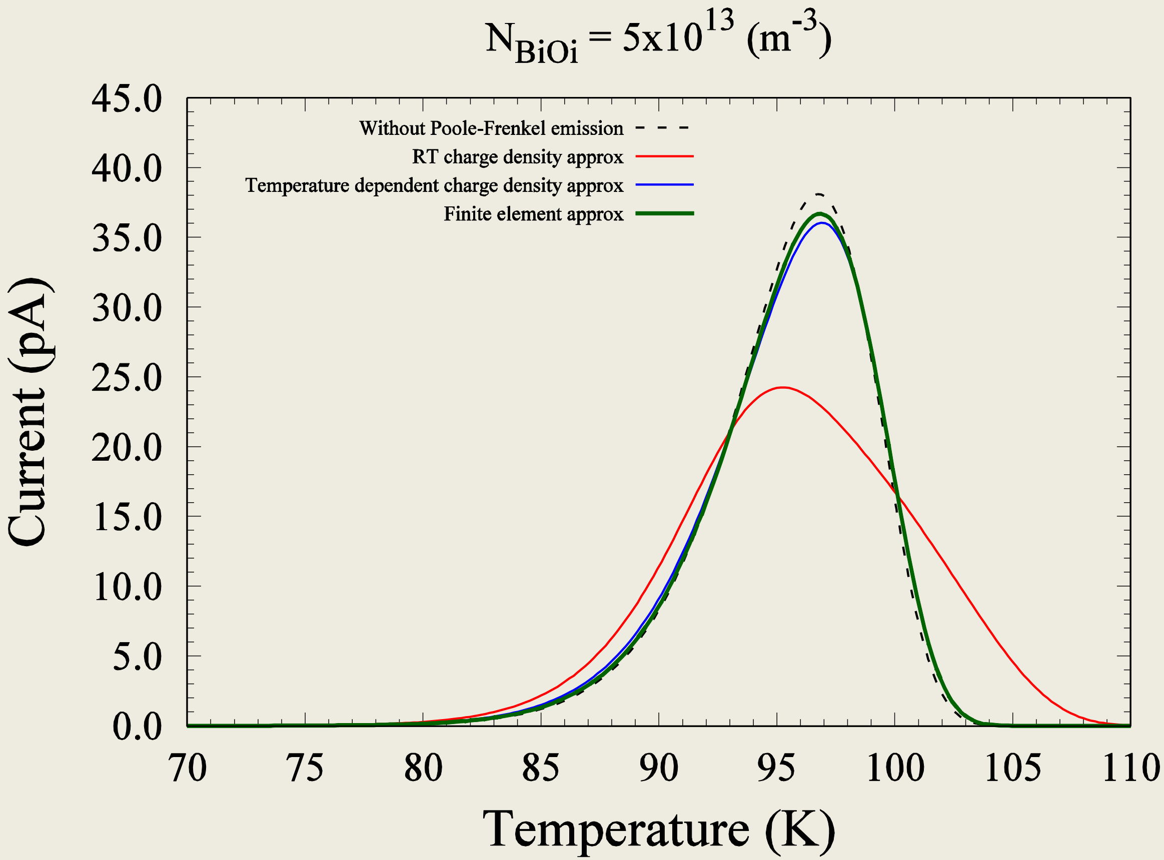
$V = 190$ (V)

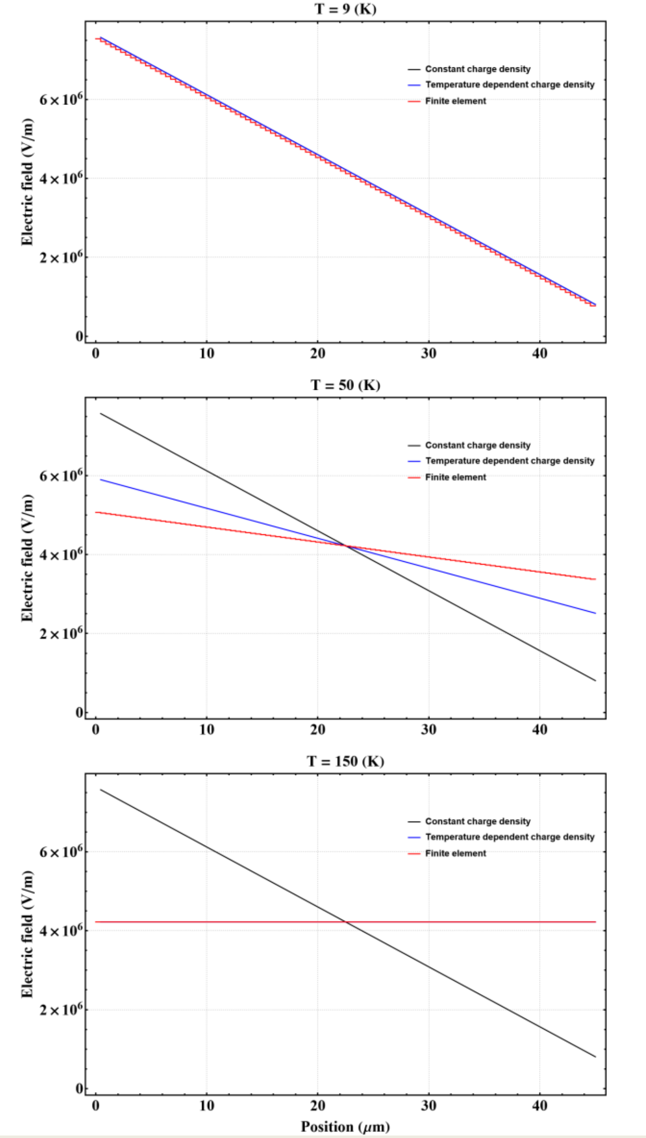
$\sigma_n = 1.05\text{x}10^{-14}$ cm^2

$E_a = 0.25$ (eV)

$E_a^0 = 0.28$ (eV)

Results: approximations comparison

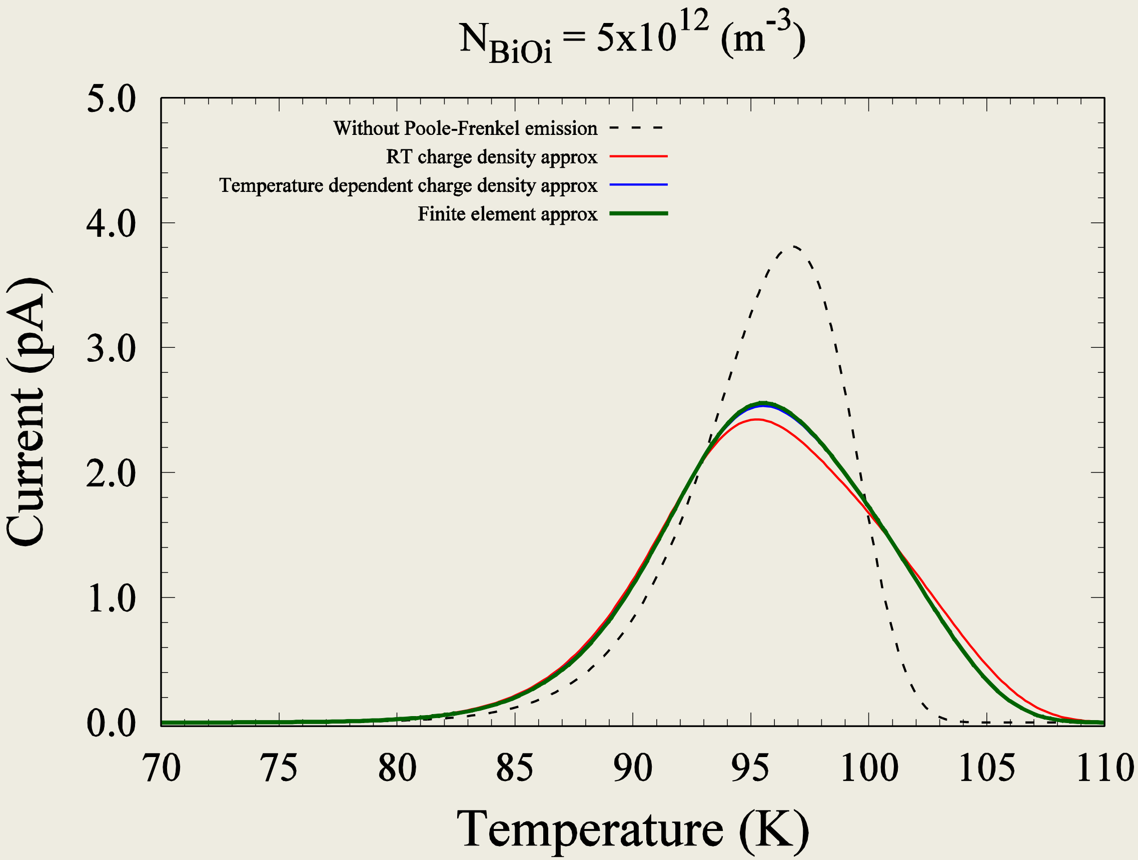


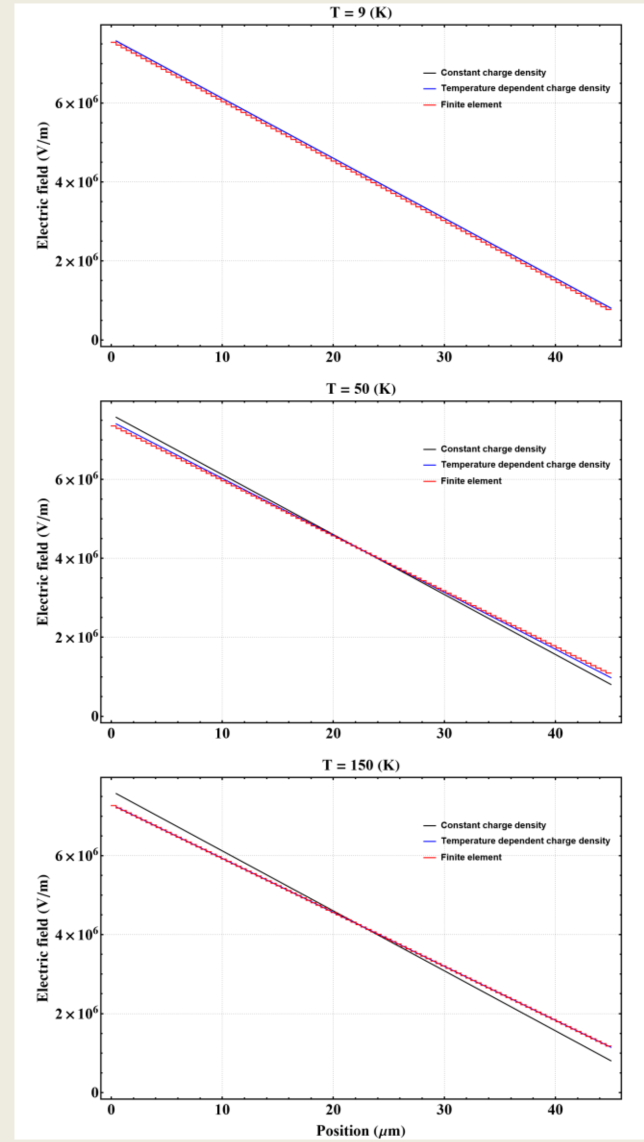


$N_a = 1x10^{14}$ (cm^{-3})   V = 190 (V)

$\sigma_n = 1.05x10^{-14}$ cm^2 $E^0_a = 0.28$ (eV); $E_a^{no\ PF} = 0.25$ (eV)

Results: approximations comparison





$N_a = 1x10^{14}\ (cm^{-3})$ $V = 190\ (V)$

$\sigma_n = 1.05x10^{-14}\ cm^2$ $E^0_a = 0.28\ (eV)$; $E_a^{no\ PF} = 0.25\ (eV)$

Atomistilor Str. 105bis, PO Box MG7, Magurele, Bucharest, Romania, 077125, Telephone : +40213690185
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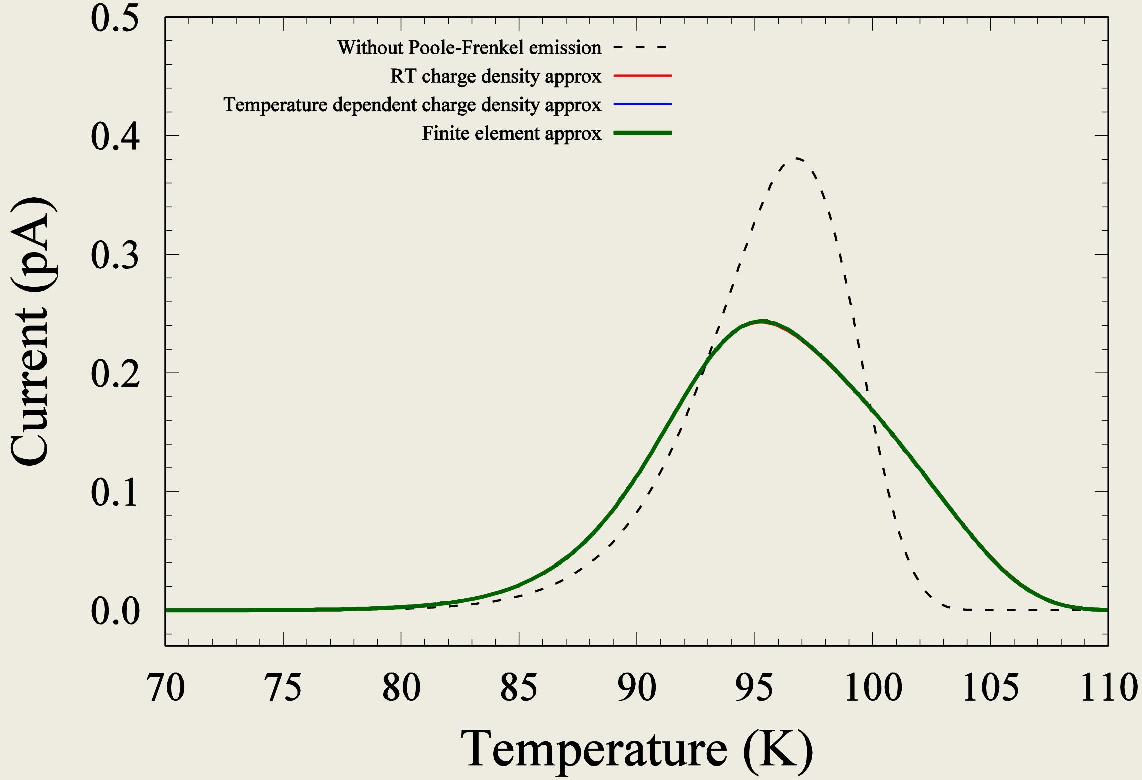
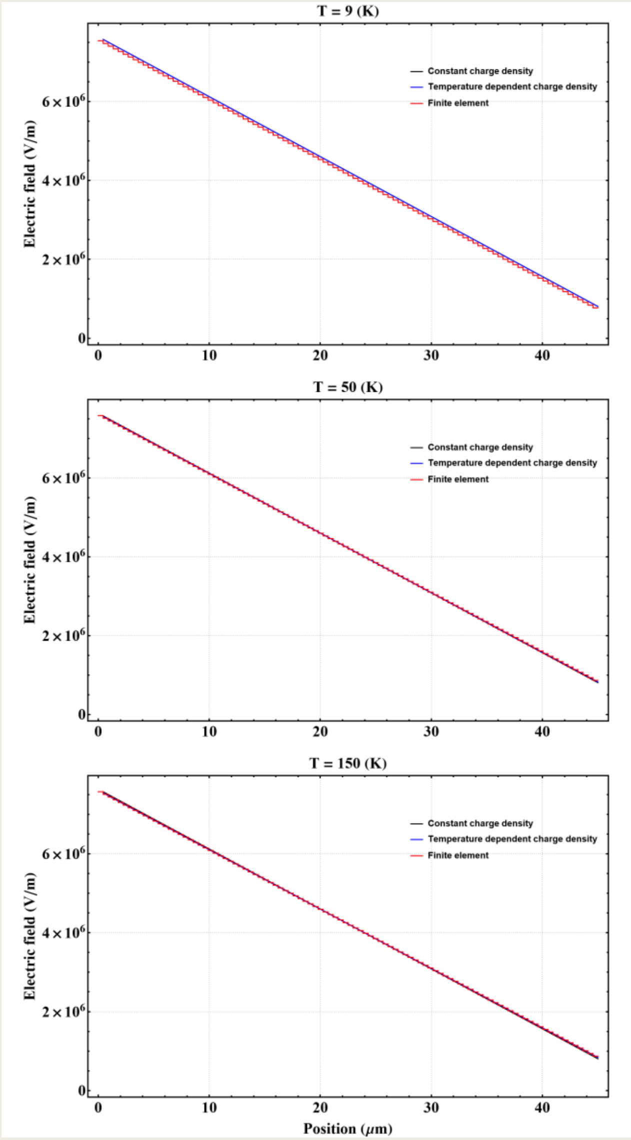
Results: approximations comparison

$N_{BiOi} = 5x10^{11}$ (m^{-3})





$N_a = 1x10^{14}$ (cm^{-3}) V = 190 (V)

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Summary and Conclusions

- TSC evaluations of Coulombic centers induced by irradiation – BiOi as example
- Poole-Frenckel formalism was accounted
- Three approximations for the electric field were investigated

- For low defect concentrations all approximations give the same result
- Differences appear for high [BiOi]

The End