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Generation current temperature scaling

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This talk is a summary of the Technical Note: A.Chilingarov, “Generation current temperature scaling” of 9.5.2011. It can be reached at

https://rd50.web.cern.ch/rd50/doc/Internal/rd50_2011_001-I-T_scaling.pdf

The Note relies heavily on the Review: M.A.Green, “Intrinsic concentration, effective densities of states, and effective mass in silicon”, Journal of Applied Physics, 67 (1990) 2944.

The current per unit area generated inside the depleted bulk can be written as:

$$J(T) = qWn_i/\tau_g$$

where q is elementary charge, W – depleted thickness, n_i – intrinsic carrier concentration and τ_g – generation lifetime.

Temperature dependence of n_i can be expressed as:

$$n_i \propto T^{3/2} \exp(-E_g/2kT)$$

where E_g is the band gap.

Assuming generation happening via a trap with density N_t and level E_t in the band gap the generation lifetime can be written as:

$$\tau_g = \tau_p \exp(\Delta_t/kT) + \tau_n \exp(-\Delta_t/kT)$$

where $\Delta_t = E_t - E_i$ (E_i is intrinsic Fermi level) and $\tau_{p(n)}$ is the trapping time for holes (electrons):

$$\tau_p = 1/N_t\, v_{thp}\, \sigma_p\ ;\ \tau_n = 1/N_t\, v_{thn}\, \sigma_n\ .$$

Here $v_{thp(n)}$ is the thermal velocity and $\sigma_{p(n)}$ - trapping cross-section for holes (electrons).

Assuming that N_t and cross-sections are independent of temperature and neglecting weak temperature dependence of the effective carrier masses the trapping times can be scaled with temperature as:

$$\tau_{p(n)} \propto T^{-1/2} \, .$$

If $\tau_p \approx \tau_n$ the τ_g dependence on Δ_t /kT is close to $cosh(\Delta_t /kT)$. Thus τ_g is at minimum and the current generation is most effective when $\Delta_t \approx 0$. For $|\Delta_t| /kT > 1.5$ the *cosh* is reduced to $exp(|\Delta_t| kT)$. Therefore the current scaling with temperature is usually expressed as:

$$I(T) \propto T^2 \, exp(-(E_g+2\Delta)/2kT)$$

where Δ is a parameter close to $|\Delta_t|$.

The temperature dependence of the current is clearly dominated by that of n_i. Thus it is crucial to know $n_i(T)$ in detail. A vast literature exists about the intrinsic carrier concentration. Here we rely on the 1990 Review by M.A.Green and concentrate on the temperature interval of ±30^{o}C most relevant to the present usage of Si detectors in Particle Physics.

The Review gives 3 experimental fits of measured $n_i(T)$ in the form:

$$n_i \propto T^m \exp(-E_a/kT)$$

where E_a is so called activation energy. In two cases m=3/2 with E_a = 0.605 and 0.603 eV. In one case m=2.365 and E_a=0.580 eV. Around T=273K this dependence may be replaced by that with m=3/2 and equivalent E_a^{eq}=0.601 eV with better than 1% accuracy in the temperature interval of ±30°C.

Combining all 3 experimental values one gets

$$E_a = 0.603 \pm 0.002 \text{ eV}$$

where uncertainty covers all available experimental data.

Thus the experimental value of the effective band gap for $n_i(T)$ is:

$$E_{ef} = 2E_a = 1.206 \pm 0.004 \text{ eV.}$$

It looks inconsistent with the actual band gap, E_g, quoted by M.A.Green as 1.124 eV at 300K and 1.137 eV at 250K.

Note however that temperature independent E_{ef} should incorporate also the temperature dependence of E_g.

Most easily this is done if $E_g(T)$ can in some temperature interval be expressed in a linear form: $E_g = E_0 - \alpha T$, where E_0 is the extrapolation of E_g to T=0. Then:

$$A \exp(-E_g/2kT) = A \exp(-E_0/2kT + \alpha/2k) = A' \exp(-E_0/2kT).$$

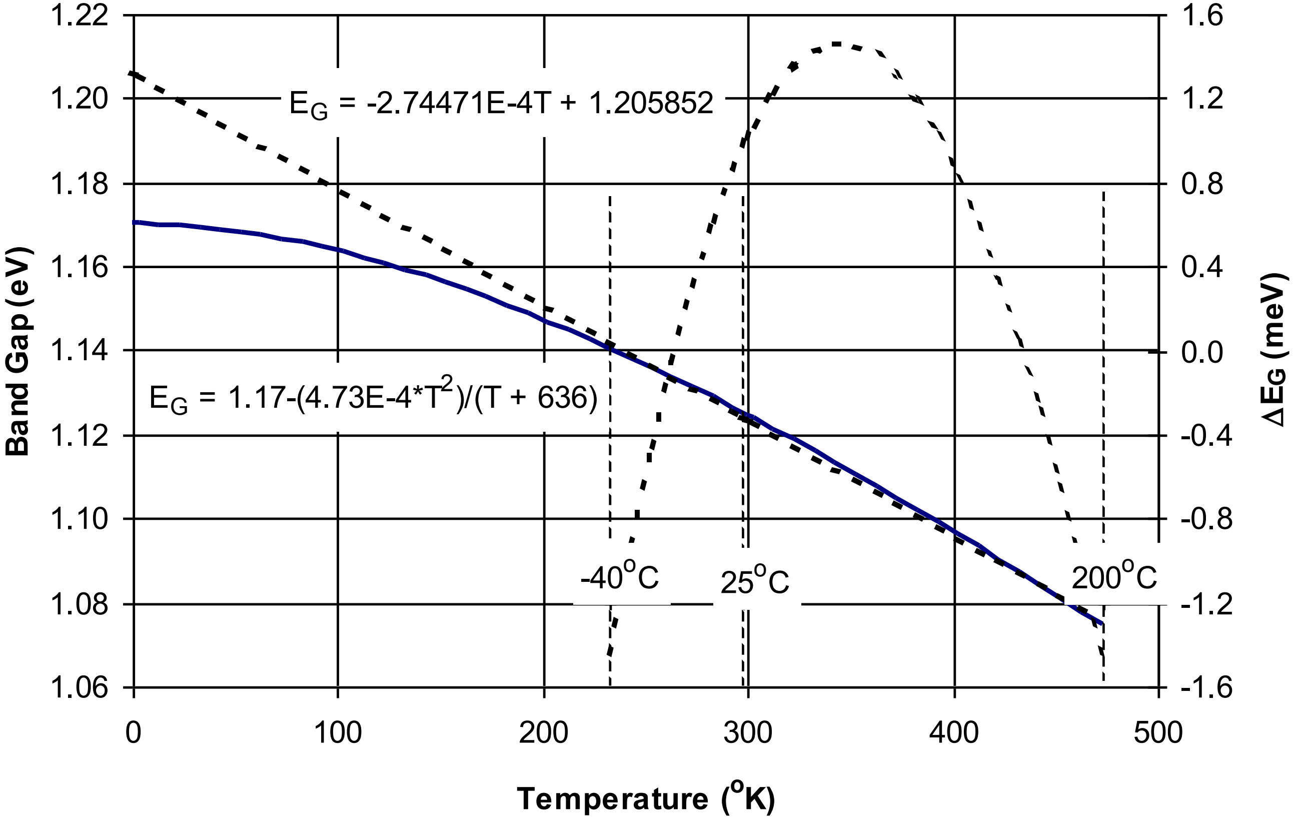
M.A.Green gives for $E_g(T)$ the linear equation valid within 1meV accuracy in the interval 250 – 415 K where

$$E_0 = 1.206 \text{ eV}$$

in perfect agreement with the experimental fits.

Thus the replacement of the <u>temperature dependent</u> band gap, $E_g(T)$, by a <u>constant effective energy</u>, E_{ef}, requires using <u>not the actual E_g</u> value at a typical temperature <u>or its average value</u> in the used temperature interval but <u>the intercept at T=0</u>, E_0, in the linear parameterisation of E_g at these temperatures. This is the property of the function $exp(-E_g(T) /kT)$.

Silicon Band Gap



This plot is taken from the 2002 talk “Band Gap Regulator Analysis” by J.B.Biard, Honeywell. (Many thanks to Graham Beck, QMUL for picking up this talk!)

From -40° to +200°C the $E_g(T)$ can be expressed within 1.5meV accuracy by a linear equation with E_0=1.206eV.

For non-irradiated silicon it is usually assumed that generation proceeds via traps close to the mid gap i.e. Δ=0. The current is then parameterised as $T^2 \exp(-E/2kT)$ with $E=E_g(T)$ or E_0.

The information on $I(T)$ for irradiated sensors is quite limited. The survey made in 1994 [A.Chilingarov, H.Feick et al., NIM A360 (1995) 432] resulted in:

$$E_{ef} = 1.24 \pm 0.06 \text{ eV},$$

which agrees with E_0=1.21 eV obtained above but has a significant uncertainty. The ATLAS SCT recommends E_{ef}=1.21 eV basing on irradiations by 24 GeV protons up to ~3 10^{14} p/cm^2.

Thus until proven otherwise the same temperature dependence with E_{ef} = 1.21 eV may be used for both irradiated and non-irradiated silicon sensors.

Conclusion

Within the range of ±30^{o}C the temperature dependence of the generation current can be described by the following parameterisation:

$$I(T) \propto T^2 \exp(-1.21\text{eV}/2kT)$$

both for non-irradiated and irradiated sensors. The difference between the effective and actual energy gaps is due to using constant E_{ef} instead of temperature dependent $E_g(T)$.

Acknowledgement

The author is grateful to Graham Beck, QMUL, UK for helpful and illuminating discussions.

Appendix

Known to the author publications with *I(T)* results in irradiated Si sensors.

1. T.Ohsugi et al., NIM A265 (1988) 105.
2. M.Nakamura et al., NIM A270 (1988) 42.
3. K.Gill et al., NIM A322 (1992) 177.
4. E.Barberis et al., NIM A326 (1993) 373.
5. H.Feick, PhD Thesis, DESY F35D-97-08, 1997.
6. L.Andricek et al., NIM A436(1999)262.

If you are aware of other publications on this topic please e-mail the reference to a.chilingarov@lancaster.ac.uk.

Many thanks in advance! Alex