4. Recombination with Defect Levels (Shockley-Read-Hall)

It is known that the presence of impurities or crystal defects in semiconductors determines the lifetime of carriers, because a modified electronic structure within the crystal will give rise to defect levels, or energy levels that do not lie near the edge of the band gap. Deep defects may lie deep within the forbidden band; these impurity levels are also called trap levels because they are traps for charge carriers\(^1\). These levels can effectively facilitate a two-step recombination process called Shockley-Read-Hall recombination where conduction electrons can relax to the defect level and then relax to the valence band, annihilating a hole in the process.

After some lengthy analysis of the dynamics involved in this process, we see that that the recombination rate \( R_T \) involved with traps is dependent on the volume density of trapping defects and the energy of the trapping level:

\[
R_T = \frac{np - n_i^2}{\tau_{h0}(n + n_1) + \tau_{e0}(p + p_1)}
\]

where \( n \) and \( p \) are the concentrations of electrons and holes respectively, \( n_i \) is the “intrinsic carrier concentration”, and \( \tau_{h0} \) and \( \tau_{e0} \) are lifetime parameters (for holes and electrons respectively) whose values depend on the type of trap and the volume density of trapping defects\(^2\). The quantities \( n_1 \) and \( p_1 \) are parameters that introduce the dependency of the recombination rate on the trapping energy level \( E_T \) as follows:
\[ n_1 = N_C \exp \left( \frac{E_i - E_c}{kT} \right) \]
\[ p_1 = N_V \exp \left( \frac{E_v - E_i}{kT} \right) \]
\[ n_1 p_1 = n_i^2 \]

These expressions are of the same form as the charge carrier concentration in terms of the Fermi energy level; what we see is that if \( \tau_{h0} \) and \( \tau_{e0} \) are of the same order of magnitude, the peak value for this type of recombination will occur when the defect level lies near the middle of the forbidden band gap. Therefore, impurities that introduce energy levels near midgap are very effective recombination centers\(^2\).

Another way in which crystal defects come into play is at the surface of semiconductors, where there are an abundance of such defects that introduce defect levels for trapping. Therefore, this process of recombination by defect levels contributes significantly to recombination at surfaces.

References
