Optical Spin Orientation

In semiconductors, non-equilibrium spin distributions can be accomplished through optical excitation, exploiting selection rules for light-induced transitions between spin states. To clarify the concept of creating spin polarization by optical means, we make reference to a direct-gap III-V semiconductor, such as GaAs. The band structure of these systems around the Γ point is sketched in Figure 9.11. The band gap E_g separates the lowest conduction band, an electron band with $L = 0$ from a valence band which originates from hole states with $L = 1$. Spin-orbit coupling splits the latter into two subbands, characterized by a total angular momentum quantum nembers $J = \frac{3}{2}$ (the upper subband) and $J = \frac{1}{2}$ (the lower subband or *split off band*), and shifted with respect to each other by the spin-orbit splitting Δ_{SO}. In Figure 9.11, these three bands are labelled according to the symmetry groups with which they transform as Γ_6^c, Γ_8^v, and Γ_7^v, respectively. The upper valence subband divides into two inverted parabolae with different curvature, reflecting different effective masses. These correspond to substates with $|m_J| = \frac{1}{2}$ versus those with $|m_J| = \frac{3}{2}$, associated with a *light hole* and a *heavy hole*, respectively. Using light in the energy interval $E_g \leq E < E_g + \Delta_{SO}$, one may induce selectively transitions from the light-hole and heavy-hole subbands into the conduction band. Spin-orbit effects within the latter, to be addressed later in this chapter, are immaterial for the present argument.

Treating the interaction between light and matter within the dipole approximation, and specifying the Hamiltonian as $\hat{H}_{int} \sim \mathbf{x} \cdot \mathbf{E}$, where the components of the coordinate vector $\mathbf{x}$ reflect the symmetries of the atomic p wave functions p_x, p_y, and p_z. For the argument presented here, any constants defining $\hat{H}_{int}$ are inessential since they do not affect the ratio of down- versus up spin excitation probabilities. This ratio has the following form:

$$\frac{|\langle \Gamma_6^c \downarrow |\mathbf{x} \cdot \mathbf{E}|\Gamma_8^v\rangle|^2}{|\langle \Gamma_6^c \uparrow |\mathbf{x} \cdot \mathbf{E}|\Gamma_8^{v\prime}\rangle|^2}, \tag{1}$$

where $\Gamma_6^c \downarrow$ ($\Gamma_6^c \uparrow$) stand for the states $|\frac{1}{2}, -\frac{1}{2}\rangle$ ($|\frac{1}{2}, \frac{1}{2}\rangle$) of the $S_{\frac{1}{2}}$ conduction band, and $\Gamma_8^v, \Gamma_8^{v\prime}$ denote states chosen from the set of the four $S_{\frac{3}{2}}$ valence band wave functions, explicitly listed in Table 9.1. The key idea underlying optical spin orientation consists in applying the selection rules valid for dipolar radiation on the transition between the valence and the conduction band. Thus, employing circularly polarized radiation with positive (σ^+) or negative (σ^-) helicity, one constrains the difference ΔM_J to +1 or -1, respectively, as illustrated in Figure 9.12. Making use of Table 9.1 and recalling that $\hat{H}_{int}$ tranforms like

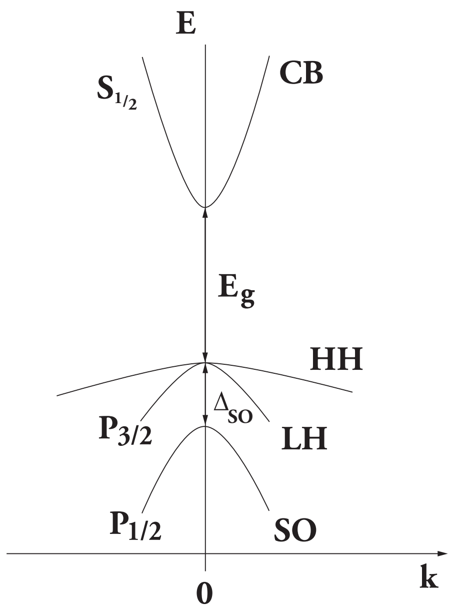

Figure 1: Sketch of the band structure of a direct-gap III-V semiconductor around the Γ point ($\mathbf{k} = \mathbf{0}$). CB stands for the lowest conduction band, described by a band wave function labeled as Γ_6^c. HH and LH denote heavy hole and light hole subbands of the highest valence band, labeled Γ_8^v, and SO the split-off band Γ_7^v.

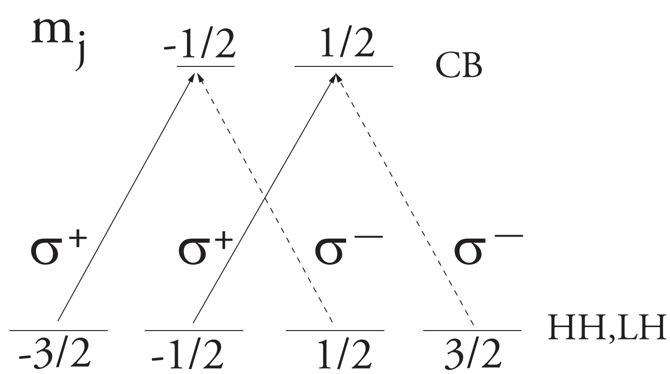

Figure 2: Scheme of the optical transitions from the heavy-hole and light-hole valence subbands into the conduction band, as induced by circularly polarized light, where σ^+ and σ^- stand for right-handed and left-handed polarization, respectively. The relative intensities of the respective transitions are indicated. The contributions of the split-off band are neglected.

Table 1: Wave functions of the lowest conduction and highest valence band at the Γ point of GaAs: symmetries and angular parts. (after [1])

Band symmetry	$\lvert J, m_J\rangle$	*Angular part of wave function*
Γ_6^c	$\lvert\frac{1}{2}, \frac{1}{2}\rangle$	$Y_{00}\uparrow$
	$\lvert\frac{1}{2}, -\frac{1}{2}\rangle$	$Y_{00}\downarrow$
Γ_7^v	$\lvert\frac{1}{2}, \frac{1}{2}\rangle$	$-\sqrt{\frac{2}{3}}(Y_{11}\downarrow + \sqrt{\frac{1}{2}}Y_{10}\uparrow)$
	$\lvert\frac{1}{2}, -\frac{1}{2}\rangle$	$\sqrt{\frac{2}{3}}(-Y_{11}\uparrow - \sqrt{\frac{1}{2}}Y_{10}\downarrow)$
Γ_8^v	$\lvert\frac{3}{2}, \frac{3}{2}\rangle$	$Y_{11}\uparrow$
	$\lvert\frac{3}{2}, \frac{1}{2}\rangle$	$\sqrt{\frac{1}{3}}(Y_{11}\downarrow - \sqrt{2}Y_{10}\uparrow)$
	$\lvert\frac{3}{2}, -\frac{1}{2}\rangle$	$-\sqrt{\frac{1}{3}}(-Y_{11}^*\uparrow + \sqrt{2}Y_{10}\downarrow)$
	$\lvert\frac{3}{2}, -\frac{3}{2}\rangle$	$-Y_{11}^*\downarrow$

$Y_{11}(-Y_{11}^*)$ for $\sigma^+(\sigma^-)$ radiation, we conclude that

$$\frac{|\langle\frac{1}{2}, -\frac{1}{2}|Y_{11}|\frac{3}{2}, -\frac{3}{2}\rangle|^2}{|\langle\frac{1}{2}, \frac{1}{2}|Y_{11}|\frac{3}{2}, -\frac{1}{2}\rangle|^2} = 3. \tag{2}$$

Comparing the probabilities for exciting an up-spin versus a down-spin state in the conduction band establishes the desired spin imbalance: As radiation with positive helicity is employed, it is three times as likely to generate a down spin than an up spin in the lowest conduction band. The initial degree of density spin polarization created in this manner is plausibly quantified by the ratio P_n between the difference and the sum of the densities of electrons with spin up and spin down:

$$P_n = \frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow} = \frac{1-3}{1+3} = -\frac{1}{2} \tag{3}$$

Conversely, the degree of circular polarization in the radiation emitted in the course of electron-hole recombination can be exploited as a measurable signature of spin polarization. It may be detected in experiment by recording the ratio [1]

$$P_{circ} = \frac{Int^+ - Int^-}{Int^+ - Int^-}, \tag{4}$$

defined as circular polarization of the photoluminescence. The symbols $\mathrm{Int}^{+/-}$ denote here the intensity of light with right-handed and left-handed polarization, respectively. With reference to transitions between the bands Γ_6^c and Γ_8^v, this ratio results as

$$P_{circ} = \frac{(n_\uparrow + 3n_\downarrow) - (3n_\uparrow + n_\downarrow)}{(n_\uparrow + 3n_\downarrow) + (3n_\uparrow + n_\downarrow)} = \frac{1}{4} \tag{5}$$

Electron-hole recombination processes and spin relaxation effects are two channels that reduce the initial degree of spin polarization, as given by Eq. (3). Both are characterized by rate constants. Adopting the expressions r and $\frac{1}{\tau_s}$ for the rates of electron-hole recombination and spin relaxation, Žutić et al. propose the following extension of formula (3) [**?**] [1]:

$$P_n = P_n(t=0)\frac{1 - \frac{n_0 n_{H0}}{n n_H}}{1 + \frac{1}{\tau_s r n_H}}, \tag{6}$$

with n (n_H) and n_0 (n_{H0}) as electron (hole) densities at $t > 0$ and $t = 0$, respectively.

[1]This result is based on two relations that involve the rate of electron-hole photoexcitation, G. Under equilibrium conditions, this rate must be compensated by electron-hole recombination, according to $r(nn_H - n_0 n_{H0}) = G$. The equivalent statement for the balance between spin creation and annihilation is: $r(n_\uparrow - n_\downarrow)n_H + \frac{n_\uparrow - n_\downarrow}{\tau_s} = P_n(t=0)G$. These relations imply Eq. (6)

Bibliography

[1] I. Žutić, J.Fabian, S.Das Sarma, Spintronics: Fundamentals and applications, Rev.Mod.Phys. 76, 323 (2004)