**Electron g-factor Engineering in III-V Semiconductors for Quantum Communications**

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**Abstract**—An entanglement-preserving photodetector converts photon polarization to electron spin. Up and down spin must respond equally to oppositely polarized photons, creating a requirement for degenerate spin energies, \( g_e \approx 0 \) for electrons. We present a plot of \( g_e \)-factor versus lattice constant, analogous to bandgap versus lattice constant, that can be used for g-factor engineering of III-V alloys and quantum wells.

The major motive for the research on III-V semiconductors has been the development of opto-electronic devices for optical communications. One of the key inventions for improved semiconductor lasers was electronic bandstructure engineering based on strained heterostructures [1]. Practical realization of quantum communications [2, 3] is expected to require entanglement-preserving photodetectors in which quantum information is transmitted by photon polarization through an optical fiber, and then transferred to electron spin in a semiconductor [4, 5]. To maintain the entanglement, the photo-detector should absorb equally into up and down electron spin states, and thus the electron g-factor should be engineered for \( g_e \approx 0 \). Fortunately, the familiar band structure engineering of effective mass can equally well control g-factor as well. There are additional requirements in Ref. 5 for moderately long spin coherence times, and for a hole g-factor \( |g_h| > 0 \), large enough to lift the Kramers’ degeneracy of the valence band. Various III-V alloys and quantum wells can be engineered to produce the right g-factor combinations.

To commence the task of g-factor engineering, we have graphed the experimental electron g\(_e\)-factors in III-V semiconductors as a function of the lattice constant in Fig. 1(a). This is analogous to the famous graph of bandgaps versus lattice constant plotted in Fig. 1(b). In these figures, we have inscribed vertical & horizontal dash-dotted lines to illustrate design preferences. The horizontal axis in Fig. 1(a) shows a requirement for zero electron g\(_e\)-factor, \( g_e \approx 0 \). The horizontal dash-dotted line in Fig. 1(b), is a preference for a bandgap of 0.8 eV, or \( \lambda = 1.55 \ \mu m \), corresponding to the optimum wavelength for fiber-optic communications, but shorter wavelengths \( \lambda = 1.3 \ \mu m \) are also acceptable for quantum communication. To balance the entanglement-preserving photodetector to a conventional InP substrate, a vertical dash-dotted line is shown

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**Fig. 1**

(a) A graph of g\(_e\)-factors for conduction electrons in III-V semiconductors as a function of lattice constant. Dots show experimental g\(_e\)-factors, solid curves show direct bandgap materials, and dashed curves show indirect bandgap materials. The vertical dash-dotted line indicates the lattice constant of bulk InP, that is normally used for optical communication devices. Bulk g\(_e\)-factors are plotted for direct bandgap materials (InP [7, 8], GaAs [9], GaInAs [10, 12], InAs [13], GaSb [14, 15], GaInSb [16] and InSb [17]), and defect or impurity related g\(_e\)-factors are plotted for indirect bandgap materials (GaP [18], AlAs [19], and AlSb [20]). All data were taken at low temperature 1.4 - 4.2°K, but Ref. 13 is taken at 30°K. (b) Energy bandgaps for the materials shown in Fig. 1(a) at temperatures between 1.4 and 4.2°K.
at lattice constant $a = 5.86 \, \text{Å}$. 

To fill in the gaps between the experimental $g_e$-factor points in Fig. 1(a), some theoretical curves were included in Fig. 1(a). The following simple formula derived from the $k$-$p$ perturbation theory [6] was used for the theoretical curves:

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g_e = 2 - \frac{2 E_g \Delta}{3 E_g (E_g + \Delta)}
$$

(1)

where $E_g$ is the energy bandgap, $\Delta$ is the spin-orbit splitting energy, and $E_p$ is the energy equivalent of the principal interband momentum matrix element. We used experimentally determined $E_g$ and linearly interpolated $\Delta$ and $E_p$ for alloys, utilizing known values for pure compounds. No fitting parameters were used. Although the formula includes only the lowest conduction band, the highest valence band, and a spin-split-off valence band, it agrees reasonably well with the experimental data. Dotted lines in the figure show the range of indirect material, where Eq. (1) is not applicable, and $g_{e,\text{direct}} \approx 8$.

The trend in both Fig. 1(a) & 1(b) is for $g_e$-factor to be more negative as the bandgap drops. The main exception is InP. InP is the only III-V to show positive $g_e$-factor at moderate bandgaps. This is because of the remarkably small spin-orbit splitting $\Delta = 0.108 \, \text{eV}$ in InP. Considering only bulk III-V semiconductors, one prefers to reduce $E_g$ down to 0.8 eV (1.55 μm), while keeping $\Delta$ no larger than 0.11 eV, in order to achieve near-zero $g_e$-factor ($E_p$ is always around 22 eV). No bulk material is readily available with these characteristics. Much more design freedom can be achieved in multilayer heterostructures. For a reliable quantitative analysis to establish a proper design, it will be necessary to take into account the effects of quantum confinement as well as the strain-induced valence band splitting to fulfill the electron & hole $g$-factor requirements of an entanglement-preserving photo-detector.

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REFERENCES


