

Development of Low Noise III-V Digital Alloys for Improved Photodetection

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Abstract: A detailed theoretical investigation of the underlying physics of low noise III-V digital alloy APDs is presented here. Based on our investigations, the criteria for developing low noise digital alloys are proposed. © 2021 The Author(s)

Recently, there has been a growing demand for low noise Avalanche Photodiodes (APDs) for applications like single photon detection and LIDAR systems. The key issue of APDs is the excess noise that results from the random nature of the impact ionization processes. The excess noise factor $F(M) = kM + (1-k)(2-1/M)$ [1]. Here k is the ratio of the hole ionization coefficient, β , to the electron ionization coefficient, α . In order to suppress excess noise one of the ionization coefficients must be much larger than the other. This makes the impact ionization process more deterministic. In the last few years, some III-V digital alloy APDs have demonstrated low excess noise. The low noise in these alloys is attributed to factors like presence of minigaps, increased hole effective mass and large energy separation between the light-hole and split-off bands. Here, we explain the role of minigaps in limiting hole ionization. Based on calculations, we propose four inequalities that can be used as design criteria for low noise digital alloy APDs.

Digital alloys are short-period superlattices in which binary constituents are stacked alternately in a periodic manner as shown in Fig. 1. The excess noise factor vs. multiplication gain for different digital alloys is shown in Fig. 2. It demonstrates that not all digital alloys have low excess noise. Experimental 8-monolayer (ML) InAlAs, 10ML AlInAsSb and 5ML AlAsSb APDs have low k values of 0.05, 0.01 and 0.005 respectively, and thus have low noise [2-4]. However, 8ML InGaAs and 8ML AlGaAs APDs have k values of 0.3 and 0.1 respectively, and they high excess noise [5,6]. InAlAs, InGaAs and AlInAsSb have small gaps in the valence called minigaps. The unfolded bandstructure in Fig. 3 shows the minigap in the light-hole band of InAlAs. The bandstructure is computed using Environment-Dependent Tight Binding model that is calibrated to state-of-the-art Density Functional Theory bandstructure and wavefunctions [7]. In theory, these minigaps prevent holes from reaching higher energies and stop hole-initiated impact ionization events by acting as tunneling barriers. The ballistic transmission vs. energy in the valence band for transverse $\mathbf{k}_\perp=0$, computed using a quasi-1D Non-Equilibrium Green's Function (NEGF) model, is shown in Fig. 4. This depicts that in the minigap regions in the growth direction, the transmission probability of carriers is very low. However, if the minigap size is smaller than the optical phonon energy, like in InGaAs which also has lower hole effective mass, it is possible to circumvent these barriers by means of phonon scattering or tunneling. The energy separation between light-hole bands and the split-off bands also acts as barriers to impact ionization of holes. Usually, holes jump to the split-off bands, which have lower effective mass, in order to move to higher energies very quickly. In AlInAsSb and AlAsSb this energy separation is quite large which also reduces the transmission probability. Based on these observations we propose four empirical inequalities, shown in Fig. 5, that can be used to evaluate low noise performance based on material parameters obtained from bandstructure calculations and phonon dispersions.

The first inequality expresses that the bandwidth to the first minigap is lower than the ionization threshold energy. Inq. (2) asserts that the optical phonon energy has to be less than the minigap size. The tunneling probability for holes to jump across the minigap or from the light-hole band to the split-off band must be low. Inq. (3) gives the inequality for the minigap and Inq. (4) represents the light-hole/split-off energy separation. The inequality values for the alloys mentioned above are given in Table I. It can be seen that they provide a good measure of the excess noise performance of the different digital alloys.

These empirical inequalities can provide a good barometer for the noise performance of digital alloys based on theoretical calculations. These can be used to band engineer new materials for signal detection in a wide range of frequencies.

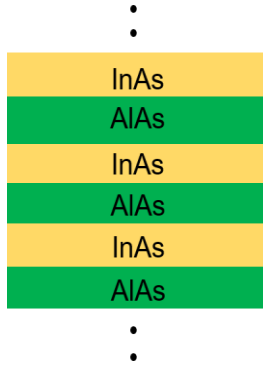


Fig. 1. Digital Alloy Structure of 6ML InAlAs consists of 3ML InAs and 3ML AlAs alternately stacked in a periodic manner. Other digital alloys are formed using similar patterns.

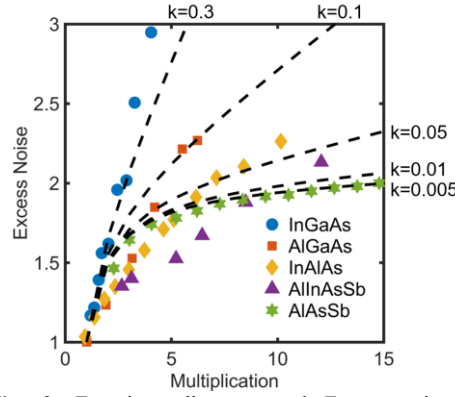


Fig. 2. Experimentally measured Excess noise vs. Multiplication gain of 6ML InGaAs, 6ML AlGaAs, 6ML InAlAs, 10ML AlInAsSb and 5ML AlAsSb is shown here [2-6]. The black dotted lines for the corresponding k 's are plotted using McIntyre's formula [1].

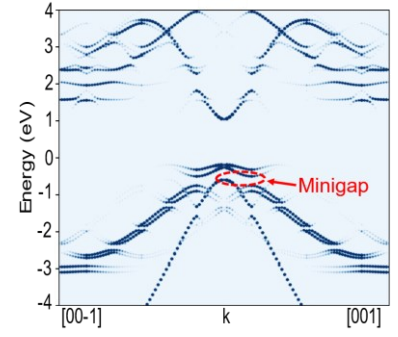


Fig. 3. Unfolded bandstructure of 6ML InAlAs computed using Environment-Dependent Tight Binding Model [7]. A minigap is circled in red.

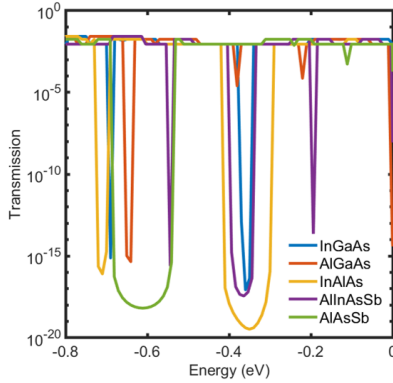


Fig. 4. Ballistic Transmission vs. Energy for all the digital alloys at $k_{\perp}=0$. Due to the minigaps there are regions of very low transmission that prevents hole from moving to higher energies in order to impact ionize.

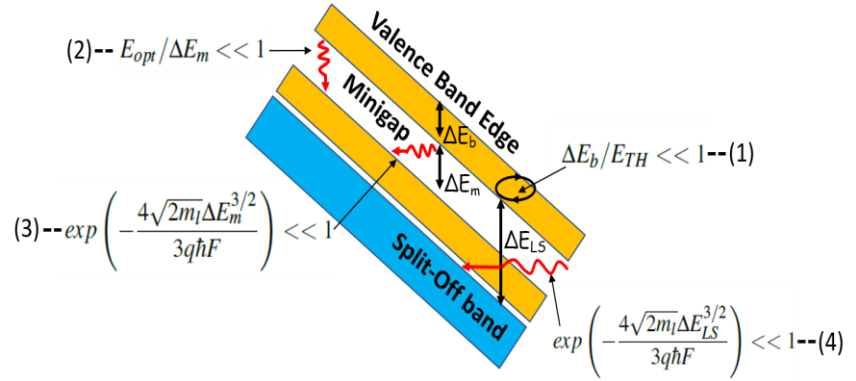


Fig. 5. Criteria for designing low noise digital alloy APDs. Inq. (1) states that the bandwidth to the first minigap is lower than the ionization threshold energy. Inq. (2) asserts that the optical phonon energy has to be less than the minigap size. The tunneling probability for holes to jump across the minigap or from the light-hole band to the split-off band must be low. These are described by Inq. (3) and Inq. (4).

Table I. The value of the design inequalities for the different digital alloys are given in the table. Here, the color green means favorable for low noise and red indicates it is unfavorable. The shades indicate the impact of the inequality in determining the ionization coefficient ratio k of the material. Dark shade indicates that the inequality has a greater impact on the value of k .

Material	Inq. 1	Inq. 2	Inq. 3	Inq. 4	k
InGaAs	0.38	1.03	0.75	1.1×10^{-5}	0.3
AlGaAs	1	∞	1	1.03×10^{-7}	0.1
InAlAs	0.16	0.33	0.0182	5.9×10^{-8}	0.05
AlInAsSb	0.37	0.18	2.25×10^{-4}	2.7×10^{-14}	0.01

Acknowledgement

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