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Flat-band pn-based unipolar barrier photodetector

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ABSTRACT

This work presents a pn-based unipolar barrier detector architecture that exhibits no band bending under zero bias. A zero-bias flat band structure is created by utilizing materials with pre-aligned Fermi levels, which prevents charge transfer across the junction and depletion layer formation. The ideal structure shows no detectable g–r, tunneling, or surface leakage currents, and is more tolerant to variations in layer composition than other barrier detector architectures.

1. Introduction

The last decade has seen the emergence of the unipolar barrier device architecture as an attractive solution for achieving high performance infrared photodetectors. An "ideal" barrier architecture detector must possess several defining characteristics: it blocks majority carrier, surface, and tunneling leakage currents; allows for unimpeded flow of minority carriers; and suppresses generation–recombination (g–r) current by avoiding depletion regions. The nBn was the first (and remains the simplest) such detector, notable for its flat band structure under zero bias, and for its greatly improved dark current characteristics compared to conventional pn photodiodes [1].

Eliminating the depletion region from a pn-based structure is a significant challenge, yet one which must be met in order to realize a similarly "ideal" design. n- and p-type materials often have Fermi levels at different absolute energies, and devices formed from such materials will therefore incorporate some degree of band bending. The resulting depletion region g–r current may degrade their performance, making these devices less than ideal. The present work addresses this dilemma by demonstrating an ideal pn-based structure where the n- and p-type materials are carefully chosen to have pre-aligned Fermi levels, so that the device structure formed by joining these materials maintains flat energy bands throughout, and thus is free of zero-bias depletion regions.

2. Background

The depletion layer and band bending in a traditional pn junction result from charge transfer across the junction, which is needed to equalize the Fermi level throughout the device structure. This equalization process must occur in order to establish thermal equilibrium between the n- and p-type materials when the absolute energies of the Fermi levels in the unjoined materials are unequal. Note that this is always the case in a pn homojunction, where the Fermi level position depends on doping. It is frequently, but not always, the case in a pn heterojunction, where material choice also plays a role. This is not an issue in an nBn, because the n-type absorber and n-type collector materials have nearly (if not perfectly) aligned Fermi levels; in either case, any substantial band bending that would tend to move the Fermi level close to the middle of the bandgap is avoided. The resulting absence of associated depletion region g–r in this flat-band structure has been well-documented [2].

3. Device architecture

The goal of the present work is to apply design principles from the ideal nBn to create a similarly ideal, flat-band pn-based structure. In general, if the n-type collector of an nBn were replaced with an arbitrary p-type collector material, one of three possible situations must be the result. These situations are illustrated in Fig. 1.

(a) The Fermi level in the isolated p-type collector material is lower than the Fermi level in the isolated n-type absorber material. The joined structure will exhibit upward band

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bending at the junction and downward band bending at the contact. The upward band bending at the junction creates a depletion region in the absorber, and the downward band bending at the contact creates a valence band barrier. The structure is identified by g–r current and increased thermal activation energy under reverse bias, and reduced thermal activation energy under forward bias.

(b) The Fermi level in the isolated p-type collector material is equal to the Fermi level in the isolated n-type absorber material. The joined structure will exhibit no band bending (under zero bias). The structure is identified by ideal, Auger-1-limited dark current, and full-bandgap thermal activation energy under both reverse and forward bias.

(c) The Fermi level in the isolated p-type collector material is higher than the Fermi level in the isolated n-type absorber material. The joined structure will exhibit downward band bending at the junction and upward band bending at the contact. The downward band bending at the junction creates a valence band barrier, and the upward band bending at the contact creates an accumulation layer. The structure is identified by increased thermal activation energy under both reverse and forward bias.

After selecting a specific material system in which to pursue this general design, some difficulty is encountered due to a lack of suitably precise information on absolute band energies. Some references exist [3], but the typical uncertainty of approximately 100 meV is too coarse for this purpose. Therefore a reasonable approach, and the one taken here, is to vary the composition of the p-type collector material among several different growths. The p-type collector material which results in the ideal band alignment can then be inferred by comparing these growths on the basis of their distinguishing performance characteristics described above.

4. Growth and fabrication

This work was performed with InAs-based materials. High-quality InAs substrates are readily available and $AlAs_{0.18}Sb_{0.82}$ is known to be an effective conduction band barrier with zero valence band offset [2]. GaSb-based materials were chosen for the p-type collector materials because the valence band of GaSb nearly aligns with the conduction band of InAs. Therefore, unintentionally-doped n-type InAs ($n \approx 10^{16}\,cm^{-3}$) and p-type GaSb ($p \approx 10^{17}\,cm^{-3}$) nearly possess the pre-aligned Fermi levels required to produce flat energy bands throughout the joined device structure.

One growth was performed with $GaAs_{0.09}Sb_{0.91}$ as the p-type collector material, which lattice-matches the InAs substrate. Exchanging gallium for aluminum has a small effect on lattice constant while increasing the bandgap of the collector layer, so it is a convenient method for varying between the possible band alignments outlined in Fig. 1. A second growth was performed with $Al_{0.12}Ga_{0.88}As_{0.09}Sb_{0.91}$ with the intent that the two growths would represent two of the three possible scenarios in Fig. 1, and one growth would represent the ideal scenario shown in Fig. 1(b).

Growths were performed by solid source molecular beam epitaxy on a Riber 32P reactor. After thermal desorption of the native oxide layer from the InAs substrate, absorber layer growth was initiated 75 °C above the InAs (001) [$(2 \times 4) \rightarrow (4 \times 2)$] transition temperature. Substrate temperature was not varied between layers, and only minimal growth stops were used (never exceeding 90 s) with the intent of preserving crystalline material quality at the interfaces.

Growths were processed into individual square mesas of varying sizes by contact photolithography and wet chemical etching. Ti/Au contacts were formed by electron beam evaporation and liftoff.

5. Device performance

The two epitaxially-grown structures were compared on the bases of dark current *J–V* characteristics, dark current thermal activation energy, and photoresponse. Each individual comparison provides partial information on the relative band alignments of the two epitaxial structures. Upon consideration of all three means for comparison, it becomes evident that the ternary collector structure possesses the ideal, flat band alignment shown in Fig. 1(b). The quaternary collector structure possesses band bending of the type shown in Fig. 1(a).

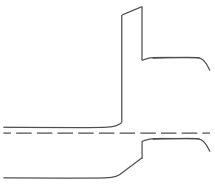
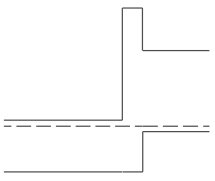
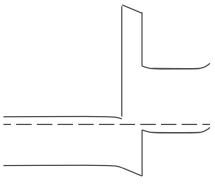
	Band Alignments in Isolated Materials	Band Diagrams of Joined Structures	Distinguishing Characteristics
(a)	$E_{F,p} < E_{F,n}$		• Depletion layer in absorber • Hole barrier at contact • Lowest valence band offset
(b)	$E_{F,p} = E_{F,n}$		• No depletion or accumulation layers • No barriers for holes • Valence band offset ≈ bandgap of absorber
(c)	$E_{F,p} > E_{F,n}$		• Accumulation layer in absorber • Hole barrier at electron barrier • Highest valence band offset

Fig. 1. Possible zero-bias pn-based band structures and their distinguishing characteristics. $E_{F,p}$ refers to the absolute energy of the Fermi level in the isolated, bulk p-type material, and $E_{F,n}$ refers to the absolute energy of the Fermi level in the isolated, bulk n-type material.