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Modeling of cryogenic capacitance–voltage (C–V) profiling for the determination of minority doping concentration in blocked impurity band (BIB) detector structures

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Abstract

A finite difference model is used to simulate the low temperature capacitance–voltage (*C–V*) profiling technique used for the measurement of minority dopant concentrations in the active layer to blocked impurity band detectors. The numerical modeling provides a complete description of the space charge distribution throughout the entire multilayer device and its response to voltage modulation during *C–V* profiling. *C–V* profiles are calculated for a range of doping gradients between the heavily doped active layer and the high purity blocking layer. We observe a range of non-linear behavior in the *C–V* profile with increasing gradient. This can result in an over-estimation of the minority doping in the active layer when applying standard analytical expressions that do not include distributed space charge effects in the data analysis.

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1. Introduction

Blocked impurity band (BIB) detectors, also known as impurity band conduction (IBC) detectors, are state of the art devices for IR detection in the wavelength range from ~5 to 40 μm [1–4]. These devices fill a need for high sensitivity detector arrays at wavelengths beyond those easily obtained with narrow bandgap detectors, such as HgCdTe, InAs or InSb. The planar, multilayer device structure also mitigates many of the limitations, such as sensitivity to ionizing radiation and transient effects, which plague conventional extrinsic photoconductors. As a result, BIB detectors are now the primary choice for mid IR detection on space-based telescopes.

The photoresponse of BIB detectors depends on the ability to collect charge from a "depletion region" in a moderately to highly doped layer. The extent of this charge collection region is determined, from a materials perspective, by the minority dopant concentration in the active layer of the device. Due to the relatively high majority level doping, hopping conduction can interfere with conventional transport techniques for determining compensation (the ratio of minority to majority doping) in a semiconductor. Therefore, materials characterization for BIB detectors requires a unique cryogenic capacitance–voltage (*C–V*) technique to spatially profile the concentration of the minority dopants.

This paper presents numerical simulation of this low temperature *C–V* measurement to determine the role of space charge and interface gradients on the device capacitance and the interpretation of the *C–V* profiling results.

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Although an idealized C–V profile can be derived analytically in the absence of interface space charge effects, exploration of the behavior under more realistic conditions requires numerical simulation of complex space charge distributions. The paper will review the operation of BIB detectors and the C–V profiling technique and then present numerical modeling results to illustrate this more complex behavior. The work builds on earlier simulations that calculate the distribution of space charge for realistic device parameters, including a range of doping in the blocking layer and growth-related doping profiles at the key materials interface [5,6]. We demonstrate here that the presence of interface-related space charge can lead to significant overestimation of the critical material parameters extracted from low temperature C–V measurements.

2. Blocked impurity band detectors

BIB detectors were developed in 1986 by Petroff and Stapelbroek to address the limitations of bulk extrinsic photoconductors [1]. They are multilayer structures, with two heavily doped contacts, an IR absorbing layer and a high purity "blocking" layer. In an n-type structure, such as Si:As or Si:Sb BIBs, all layers are n-type. However, the absorbing, or active layer can be more heavily doped than in a conventional photoconductor because the high purity layer "blocks" the path for dark current associated with hopping conduction in the more heavily doped material. The photogenerated carriers travel through the conduction band, so the device is able to take advantage of the higher absorption coefficient associated with increased doping without the deleterious effects of increased dark current. A complete description of BIB devices can be found in several reviews of detectors for the infrared region of the spectrum [7,8].

In operation, n-type BIBs are biased with a positive voltage on the blocking layer contact. Photogenerated carriers are collected from a "depletion region" adjacent to the blocking layer. Unlike a traditional pn junction, the depletion region is depleted, not only of free carriers, but also of ionized majority dopant sites. The extent of this region, as measured by a depletion width w, is given by:

$$w = \left(\frac{2\varepsilon\varepsilon_0}{qN_{\min}}|V_{\mathrm{b}}| + t_{\mathrm{b}}^2\right)^{1/2} - t_{\mathrm{b}}, \qquad (1)$$

where V_{b} is the applied bias, $\varepsilon\varepsilon_0$ is the dielectric constant, q is the charge, $N_{\min}$ is the minority doping concentration and t_{b} is the thickness of the blocking layer, which is assumed to be space charge neutral. For a given applied voltage, the depletion width, and hence the amount of current collected, is inversely proportional to the square root of the minority doping concentration. This is because the concentration of space charge in the active region under bias is, to first order, equal to the concentration of minority dopants. The lower the minority dopant concentration, therefore, the greater the extent of the depletion region.

3. Low temperature C–V profiling

An important component of characterization of BIB structures, is the determination of this minority doping concentration, since it is the critical material parameter that affects device responsivity. In uniform bulk samples or epitaxial layers, compensation (the ratio of minority to majority doping concentration) is generally measured with variable temperature Hall effect. Because the minority doping concentration affects the statistics of majority carrier recombination, its value can be determined from variations in the slope of an Arrenhius plot of the majority carrier "freeze-out" curve [9]. However, this technique cannot generally be applied to multilayer structures and is also difficult to interpret in more heavily doped material, where hopping conduction plays a role. Instead, a unique cryogenic C–V approach is used to measure minority doping directly within the BIB device structure. This technique is sometimes referred to as cryogenic capacitance versus voltage analysis (CCVA) [10].

In standard room temperature C–V profiling, one assumes that the minority dopant sites are fully compensated and that the temperature is high enough to allow for full ionization of the majority dopants. In this case, the space charge in the depletion region is given by $N_{\mathrm{maj}} - N_{\min}$. This technique is applied routinely to measure net majority carrier doping in metal-semiconductor structures [11].

In the low temperature application to a BIB structure, the temperature is reduced to the point where the majority carriers are neutral, except for the concentration that is compensated by minority type dopants. Under bias, carriers move via hopping conduction to fill the ionized majority carrier sites, creating a space charge concentration in the depletion region of the active layer that is equal to the minority carrier concentration. The capacitance, C, can be written as:

$$C = \frac{\mathrm{d}Q}{\mathrm{d}V} = \frac{\varepsilon\varepsilon_0}{\sqrt{\frac{2\varepsilon\varepsilon_0}{qN_{\min}}|V| + t_{\mathrm{b}}^2}}. \qquad (2)$$

As in standard C–V profiling, one plots $1/C^2$ versus V and the rate of change (the slope) is given by:

$$\frac{\mathrm{d}(\frac{1}{C^2})}{\mathrm{d}V} = \frac{2}{q\varepsilon\varepsilon_0 N_{\min}}. \qquad (3)$$

The minority doping therefore can be determined by a measurement of the slope as a function of applied bias, which corresponds to a measure of the space charge at various positions corresponding to the edge of the depletion region. The primary assumption that underlies the derivation of Eq. (3) is that the dominant space charge in the device is the space charge associated with the minority doping in the active layer – i.e. in the region where the depletion region is being modulated. For a BIB structure, this means an assumption that space charge in the blocking layer is negligible. In this work, we present numerical simulations of the low temperature C–V profiling technique for BIB