Spatial Modulation of the Dielectric Permmittivity and its Effect on the Spectral Responsivity of Heterodimensional Photodetectors

Francisco Castro* and Bahram Nabet**

*Motorola Labs, DigitalDNA Systems Architecture Lab
Schaumburg, IL, USA, castro@labs.mot.com
**Drexel University, Electrical and Computer Engineering Department
Philadelphia, PA, USA, nabet@ece.drexel.edu

ABSTRACT

Spectral photocurrent measurements on AlGaAs/GaAs heterodimensional detectors show a peak near the absorption edge of GaAs under low incident power and at high biasing levels. Previous work has attributed similar results to the Franz-Keldysh spectral modulation produced near the heterointerface. We expand on those results to the specific case of heterodimensional devices and present a new analytical model that demonstrates that the characteristics of the spectral response result from a spatial modulation of the complex dielectric permmittivity.

This model demonstrates that the spatial modulation of optical properties arises from the non-uniform nature of the electric field profile and from the variation in quantum confinement in the GaAs layer. In addition, biasing conditions determine the origin of collected optically generated charges producing a resonance near the GaAs absorption edge when these charges come from regions with low electric field strength.

Keywords: AlGaAs/GaAs heterointerface, non-uniform electric field, dielectric permmittivity, Franz-Keldysh, spatial modulation.

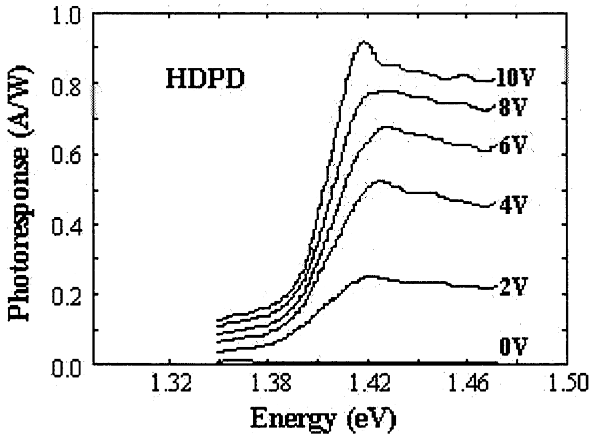

Figure 1: Spectral responsivity of a heterodimensional photodetector.

1 INTRODUCTION

The development of novel AlGaAs/GaAs photodetectors based on heterodimensional contacts have proved significant because of considerable improvements in dark current behavior [1]. Spectral measurements are needed to provide a general characterization of these devices and to probe the physical effects that heterodimensional contacts have on dark current levels. By taking advantage of the fact that these detectors can detect extremely low incident powers it is possible to minimize perturbations in the system produced by the probing light source. Figure 1 shows the spectral photoresponse of a heterodimensional photodetector implemented using a metal-semiconductor-metal (MSM) structure. As expected there is a slight peak in the response near the absorption edge of GaAs; what is unusual is the more pronounced response at higher biasing conditions, indicating that some spectral resonance effect is taking place in the device. This behavior is either the result of the presence of heterodimensional contacts in the device's structure or, a more likely scenario, is an inherent conduct of the AlGaAs/GaAs heterostructure which has become apparent because of the low incident power probing that is possible with the heterodimensional photodetector.

Previous spectral measurements of AlGaAs/GaAs heterostructures were based on photoreflection and electroreflection tests, which neglect the effect that photogenerated charge collection can play in the spectral response [2]. Nonetheless, these studies and others have indicated that the dominant phenomena in the absorption process for AlGaAs/GaAs heterostructures is the Franz-Keldysh effect produced by the presence of a electric field near the heterointerface [3,4].

In this paper we introduce a new model that describes the spectral response of heterodimensional devices based on a localized variation of the Franz-Keldysh effect. This model makes use of analytical tools developed to accurately describe the electric field profile and energy quantization effects on the absorption coefficient. We also produce a spatial mapping of the complex dielectric permmitivitty which shows that spatial modulation of the optical properties in the GaAs layer produce the enhanced response

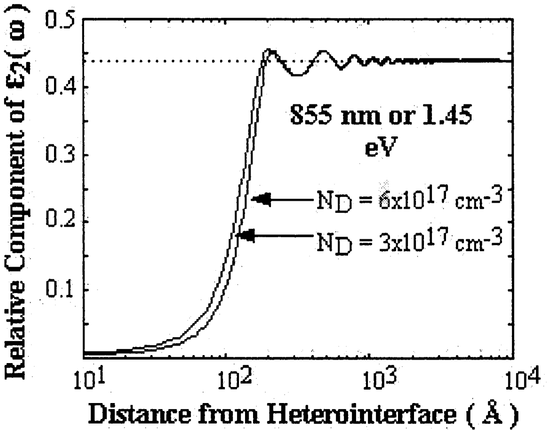

Figure 2: Spatial variation of the complex dielectric permmittivity.

under high biasing conditions when photogenerated charge collection effects are emulated.

2 PHOTORESPONSIVITY MODEL

With the aid of semiconductor modeling tools it is possible to generate some of the spectral behavior seen in heterodimensional photodetectors measurements. However, detailed analytical representations can be produced that simplify and reduce computational demands while providing a clearer picture of the physical phenomena that dominate the absorption process. For this reason an analytical model has been developed for the electric field profile at the heterointerface and tested using SILVACO's device physics simulator. This result is then used to model local variations in optical properties throughout the GaAs layer by segmenting the layer into non-uniform sublayers. From these results is possible to generate an aggregate absorption spectra of the device over the entire absorption layer with an additional degree of freedom provided by the depth of the charge collection process due to biasing conditions.

2.1 Non-uniform Electric Field

The Franz-Keldysh effect is generally modeled as a modulation in the transition between energy bands under the presence of a uniform electric field. Because the electric field produced near the heterointerface is monotonically varying it can be argued that localized calculations of the optical properties can be performed using the general description provided by the Franz-Keldysh model. This requires that the electric field's spatial strength profile is known. For this an accurate model of the sheet carrier density inside the quantum well near the interface was developed which allows for a simple yet accurate expression for the non-uniform electric filed profile to be applied to general design cases [5].

2.2 Spatially Varying Dielectric Permittivity

By using the local model of the Franz-Keldysh effect we are able to generate a spatial mapping of the absorption coefficient inside the GaAs layer. However, to accurately model spectral photogeneration it is necessary to compute the spatial profile of the complex dielectric permmittivity from the absorption coefficient. This calculation is computationally intensive but it is possible to make use of the symmetry provided by the Kramers-Kronig relations to implement a Discrete Hilbert Transform (DHT) version in order to significantly reduce computational requirements [6].

Figure 2 shows a spatial mapping of the imaginary component of the complex dielectric permmittivity for various doping concentrations of the AlGaAs donor layer at a spectral wavelength of 855nm generated by using a DHT based technique. The dashed line is the value for GaAs without any perturbations while the solid lines clearly show a spatial modulation produced by the mapping of the non-uniformity in the electric field to the optical properties of the material. The rather small value near the interface reflects the well quantization effect that has been included in the model, i.e., the bandgap enhancement produced by well quantization reduces light absorption near the interface at certain optical wavelengths. Calculations for other wavelengths would produce different spatial modulations but they would all approach the unperturbed value for GaAs far away from the interface where the electric field strength is minimal.

2.3 Charge Collection Model

Once a spatial mapping of the complex dielectric permmittivity can be easily generated for any spectral wavelength a complete simulation of photogenerated carrier collection can be performed. The absorption layer is first segmented into a fixed number of layers that provide enough discretization as to make the analysis feasible but not so that the computational demands make it unpractical. In this case the GaAs layer was divided into 512 segments of different thickness with thinner segments near the interface where electric field strength varies more rapidly. A multilayerd optical matching approach was applied to determine the amount of incident power that would be absorbed by each segment based on the optical properties that the segment would have when considering the field strength at that location.

With the number of photogenerated carriers in each segment computed an assumption is made that all charges that lie within the depth of the depletion layer produced by the lateral (heterodimensional) contacts would be collected while those outside would not be. This is, in effect, the most significant difference in the analysis when compared to photoreflection and electroreflection measurements, but one that could not be made without the detailed model so far described.

3 SPECTRAL SIMULATION

The results of spectral simulations on AlGaAs/GaAs heterostructures are shown in Figure 3 and Figure 4. The biasing conditions in these figures were chosen so as to be equivalent to the lateral fields produced by the 10V, 6V, 4V, and 2V measurements performed on the heterodimensional photodetector of Figure 1. The solid and dashed lines represent different doping concentrations in the AlGaAs donor layer which clearly are not very significant except for low biasing conditions and in the case where well quantization has been included in the overall model. As with the experimental results of Figure 1, only at high biasing conditions does a significant peak in the response is achieved, supporting the idea that it is the spatial modulation produced in the optical layer that produces this resonance. Under low biasing conditions the charges generated near the AlGaAs/GaAs interface, where the absorption spectrum spreads out due to the electric field variation, the absorption edge of the GaAs is not dominant in the aggregate collection of charges which produces the spectral response. For high biasing conditions, where a large number of charges are collected from regions where the electric field does not modulate the optical properties, the absorption edge of GaAs dominates the spectral response of the heterodimensional photodetector.

4 CONCLUSIONS

Heterodimensional photodetectors have the attractive property of producing discernable photocurrent responses under extremely low optical powers because of their low dark current behavior. Spectral measurements produced under these conditions have shown that the optical absorption process in the AlGaAs/GaAs heterostructure requires a spatial modeling of the optical properties in the GaAs layer. Additional considerations such as an accurate description of the electric field profile, techniques for calculating the complex dielectric permmittivity, quantization effects in the bandgap profile, and photogenerated charge collection mechanisms need to be integrated into a model to produce a more accurate representation of the dominant physical effects.

The model presented shows, in a simple fashion, the real effect of the non-uniform electric field in shaping up the spatial profile of the absorption layer's optical properties and their direct impact in the spectral response of heterodimensional photodetectors.

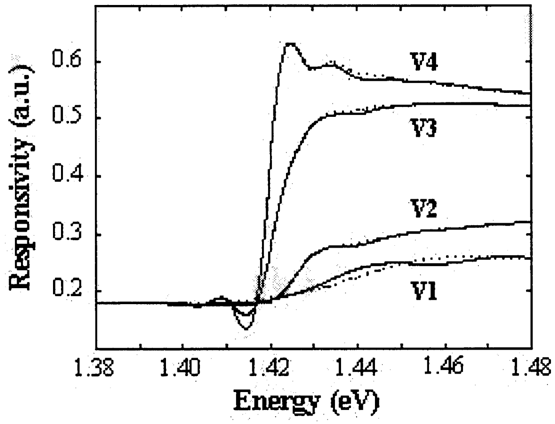

Figure 3: Generated spectral behavior not including energy quantization effects.

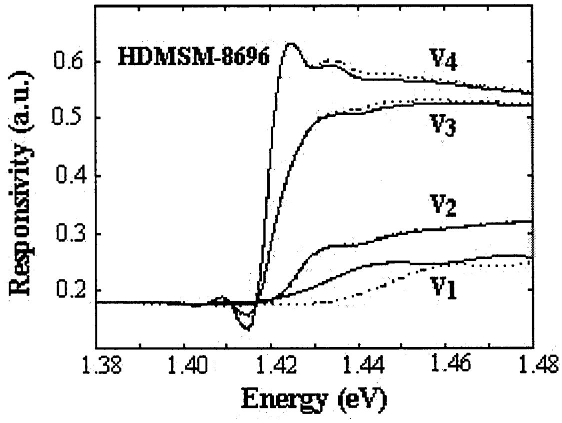

Figure 4: Generated spectral behavior with energy quantization effect.

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