Simple Electroabsorption Model for Germanium Quantum Well Devices

Rebecca K. Schaevitz[1]*, Elizabeth H. Edwards[1], Ross M. Audet[1], Yiwen Rong[1], Shen Ren[1], Stephanie A. Claussen[1], Emel Taşyürek[1], Jonathan E. Roth[2], James S. Harris[1], and David A. B. Miller[1]

(1) Edward L. Ginzton Laboratories, Stanford University, Stanford, CA 94305-4088, USA

(2) Aurrion, LLC, 5385 Hollister Ave #207, Santa Barbara, CA 93111, USA

*rschaevitz@stanford.edu

***Abstract*—We present a simple electroabsorption model for germanium quantum wells to facilitate optical modulator design. We show this model is valid for a range of well sizes with an increased exciton-enhanced absorption for thinner wells.**

Keywords- interconnects; optoelectronics; electroabsorption;

I. INTRODUCTION

Silicon-germanium/germanium (SiGe/Ge) quantum well (QW) electroabsorption-based devices provide a platform for significant improvement to on-chip optical interconnects. Models such as tight-binding and k.p are typically used to predict the absorption spectrum of such devices, which employ the quantum-confined Stark effect (QCSE) [1,2]. While these models have significant benefits for some major aspects of the problem, other important phenomena such as exciton enhancement are omitted. Additionally, these simulations can often be computationally intensive making device design far more difficult. In this paper, we will present a simple electroabsorption model for the SiGe/Ge QWs. This model is a composite of each of the major physical effects present in the material, such as well width fluctuation, indirect absorption, the Franz-Keldysh effect (FKE), broadening of the absorption from lifetime or other causes, exciton-enhancement, and non-uniform electric field, and uses the simplest reasonable model in each case. From this model, it is quite clear which effects are dominant in the absorption profile, leading to a very simple, but effective model, which can be used to optimize the device design for low-power optical modulators.

II. THEORY

To model the electroabsorption spectrum for the QCSE in SiGe/Ge QWs, the confinement energies for the individual electron- and hole-confined states are first determined using a tunneling resonance method as in [3]. The overlap between the electron and hole wavefunctions under different applied electric fields gives the basic step height for each transition between valence and conduction sub-bands. To accommodate some of the excitonic effect, this step is then augmented by the 2D Sommerfeld enhancement factor,

$$S_{2D}(\varepsilon) = \frac{2}{1+e^{-2\pi/\sqrt{\varepsilon}}}, \quad (1)$$

where ε refers to the energy normalized in Rydbergs above the start of each step, $\sqrt{(\hbar\omega - E_{step})/R_y}$. This factor gives a reasonable approximation to the effect of electron-hole Coulomb correlation on transitions above the effective bandgap.

Convolving with a Gaussian spectral broadening function smoothes out the transition step and the addition of a 1s Gaussian-shaped exciton peak positioned just below the energy of the start of each step gives the full modeled QW spectra [4,5]. The 1s Gaussian-shaped exciton peak contribution falls off faster with field than the reduction of the step height as expected by a reduced lateral Coulomb confinement of the displaced electron-hole pair. Since the same physical phenomena, such as carrier lifetime [6] and well width fluctuation [4], affect the line width of the step and 1s exciton, both Gaussians use the same parameter, σ, which increases slightly with electric field.

Following the absorption profile just described for the QW spectra, other effects, such as indirect absorption, non-uniform electric field, and FKE are included. For SiGe-based modulators, indirect absorption significantly affects the contrast ratio as well as the insertion loss and is therefore added to the model using the approach of Ref. [7]. The valence band energies are calculated from the tunneling resonance model. Temperature induced strain effects are included following [8]

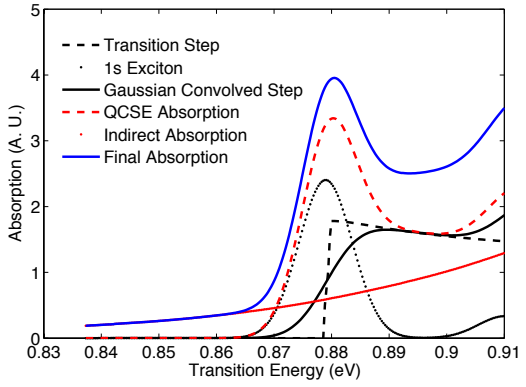

Figure 1. Various components adding up to the electroabsorption profile

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and the indirect band gap is determined from the known behavior in bulk materials. FKE absorption in the intrinsic region was calculated, but found to be insignificant. Lastly, electric field non-uniformity was included by averaging spectra for a range of electric fields present at a given applied voltage as calculated from capacitance-voltage (CV) measurements. Fig. 1 shows the summation of each of these effects leading to an absorption profile for a single electric field.

III. Results and Discussion

Using the simple model described in the theory section, we have compared the results against experimental data for two $Si_{0.15}Ge_{0.85}$/Ge QWs grown under different conditions that slightly alter the strain in the material [8]. Figure 2 shows a 9.9nm well grown at 400°C while Fig. 3 shows a 16.1nm well grown at 500°C. The QWs are embedded in the intrinsic region of a p-i-n diode for electroabsorption measurements. The electric field non-uniformity within the structure is calculated from CV measurements and has a span of ~6000 V/cm for a given applied voltage. The material compositions modeled correspond to those presented in [3] using well sizes of 9.9nm and 16.1nm. Figs. 2 and 3 show the model compared to different average electric fields.

The simple model gives very good agreement for the two well widths grown under different conditions with the largest adjustment in the 1s Gaussian exciton peak height being almost twice as large for the smaller well. This difference is expected, as the experimentally determined absorption from the thinner well sample was almost twice the magnitude compared to the larger well. A smaller effect is the spectral broadening parameter, σ, where we find this parameter decreases slightly for larger wells as expected if there is a contribution from a fixed amount of well thickness variation. (The same amount of well width fluctuation gives larger variations in confinement energy for thinner wells.) Given the known mixing of the s- and p-like unit cell states away from zone center, it is expected that the overall absorption will not exactly match the overlap step prediction at higher energies when using our simple model, and this effect could be included as a future sophistication. However, for the purpose of designing a modulator with this material, this simple model can be used to optimize the quantum well materials.

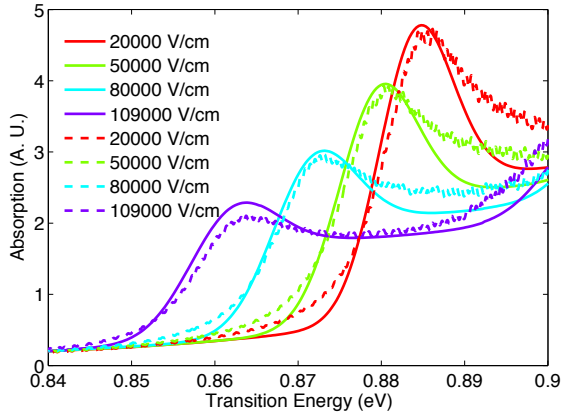

Figure 2. Absorption spectrum of a 9.9nm QW grown at 400°C experimental (dashed) vs. model (solid) for three applied electric fields

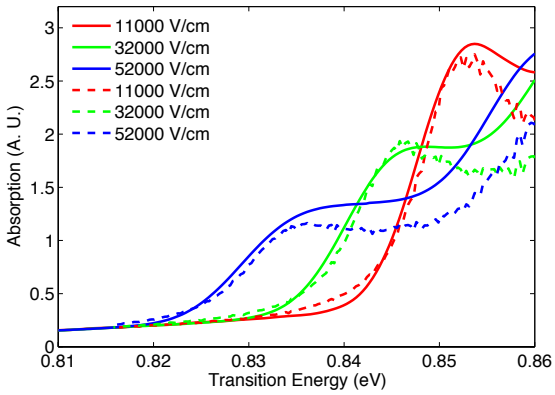

Figure 3. Absorption spectrum of 16.1nm QW grown at 500°C experimental (dashed) vs. model (solid) for three applied electric fields

IV. Conclusion

We have created a simple model that takes into account the various major physical effects present in the SiGe/Ge QW material system and effectively fits the E1-HH1 transition for two well sizes grown under very different conditions. It is clear that for smaller wells, there is an enhanced absorption due to excitonic effects. While more sophisticated models exist for some aspects, the benefit of this model is that it incorporates all of the relevant physical effects that can be present in experimental structures, especially the exciton enhancement. Consequently, this model can also determine the relative magnitude and importance of each of these effects. From the material grown in this analysis, FKE showed little effect on the final absorption spectrum, whereas indirect absorption, spectral broadening and the 1s exciton played a significant role.

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