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The sub-monolayer quantum dot infrared photodetector revisited

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HIGHLIGHTS

- The sub-monolayer quantum dot infrared photodetector (SML-QDIP) is re-examined.
- Original device normal-incidence response was attributed to 3D quantum confinement.
- Modeling shows normal-incidence response is really due to optical cavity scattering.
- Modeling suggests new designs with improved intrinsic normal-incidence absorption.

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ABSTRACT

The sub-monolayer quantum dot infrared photodetector (SML-QDIP) was proposed as an alternative to the standard QDIP based on Stranski–Krastanow (SK) quantum dots. Theoretical modeling indicates that the normal-incidence photo-response observed in the initial SML-QDIP devices, originally attributed to 3D quantum confinement effect, is most likely the result of optical cavity scattering. Modeling results also suggest candidate SML-QDIP structures with improved intrinsic normal incidence absorption.

1. Introduction

The submonolayer (SML) quantum dot infrared photodetectors (QDIP) [1] was introduced as an alternative to Stranski–Krastanow (S–K) quantum dot based QDIPs [2]. In this paper we re-examine the original experimental data and their interpretation, and also present simulation results which suggest device design improvement. Section 2 discusses the SML-QDIP concept and highlights results from the original implementation. Section 3 reconsiders the interpretation of the data. Section 4 shows theoretical results that clarifies the QDIP operation, and suggests how the SML-QDIP performance could be improved. Section 5 provides discussions and summary.

2. Submonolayer quantum dot photodetector background

It has been predicted that quantum dot infrared photodetectors (QDIPs) with small dot size, high dot density and uniformity could outperform quantum well infrared photodetectors (QWIPs) [3,4], in part due to their normal incidence absorption properties and reduced thermal dark current generation due to decreased optical phonon scattering. Variations on the basic QDIP structure, including the dot-in-the-well (DWELL) [5] and the confinement enhanced DWELL (CE-DWELL) [6], have resulted in increased versatility and improved performance. QDIPs usually are based on quantum dots formed via the Stranski–Krastanow (S–K) growth mode [2]. Fig. 1 illustrates an InAs/GaAs QDIP structure with S–K QDs, typically formed by depositing 2–3 monolayers of InAs on lattice mismatched GaAs substrates. The first monolayer or so of the InAs deposited forms a wetting layer, which makes up a significant fraction of the InAs deposited for dot formation. But because wetting layer is a purely two-dimensional (2D) structure (essentially a thin quantum well), it does not contribute to normal incidence absorption. The dimension of the quantum dot that is the most relevant to normal-incidence absorption is the lateral quantization dimension: specifically, the base width of the quantum dot. We suggested that monolayer-thick, isolated InAs islands embedded in GaAs could still retain the key properties of normal-incidence absorption and reduced LO phonon scattering for 3D confined structures. Such structures are in fact routinely made by depositing fractional (typically 1/2 or 1/3) monolayers of a semiconductor on top of a lattice mismatched substrate [7]. In particular, the

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InAs/GaAs submonolayer (SML) QD system is well-characterized [8], and is used in vertical cavity surface-emitting lasers (VCSELs) [9] and disk lasers [10]. The use of SML QDs instead of S–K QDs has the advantage that, whereas typically 2–3 monolayers of InAs is needed for a single layer of S–K QD formation, only 1/3–1/2 monolayer is needed for SML QD. The reduction in the amount of lattice mismatched material (InAs) used per layer of QD formation means that the material is less strained, and therefore more stacks of QD layers can be included. SML QDs can be realized in a variety of insert/host matrix semiconductors [11,12]. The lateral dimensions of SML QDs can be quite small (5–10 nm), and the dot areal density can be quite high [8,11]. By controlling the inter-layer spacer thickness, multiple SML-QD layers can be stacked with vertical alignment [13], yielding device design flexibility. These considerations led us to the concept of the SML-QDIP [1] as an alternative to S–K QD based QDIPs.

Fig. 2 shows the normal-incidence and 45°-incidence responsivity measured for a typical SML QDIP structure consisting of InAs SML QD layers embedded in GaAs quantum wells (QWs) surrounded by $Al_{0.16}Ga_{0.84}As$ barriers. The structure, grown by IQE, contains 30 quantum wells, with 51 Å well width, and $n = 5 \times 10^{17}\,cm^{-3}$ doping. Each quantum well contains two symmetrically placed SML QD layers, located at approximately 14 Å from the center of the quantum well, as illustrate in the left panel of Fig. 3. For this sample (SMD 1–2), the responsivity peak occurs at ~10 μm, with peak values of 178 mA/W and 543 mA/W at −2.25 V for the normal- and 45°-incidence configurations, respectively. The ratios of the normal incidence to 45° incidence response (η_{nor}/η_{45}) under −0.75 V and −2.25 V applied bias are 43% and 33% respectively. These values are considerably higher than that found for the typical GaAs/AlGaAs QWIP (~10%), and we attributed this to the 3D nature of the wave function induced by the presence of the InAs SML QDs. Details of single-element detector results, as well of focal plane array results, have been presented in Ref. [1]. Since our original publication, the SML-QDIP concept, including the suggested multi-layer QD stack enhancement [1], has been adopted and demonstrated by other researchers, who reported superior normal-incidence detection properties than QDIP structures based on S–K QDs [14–16].

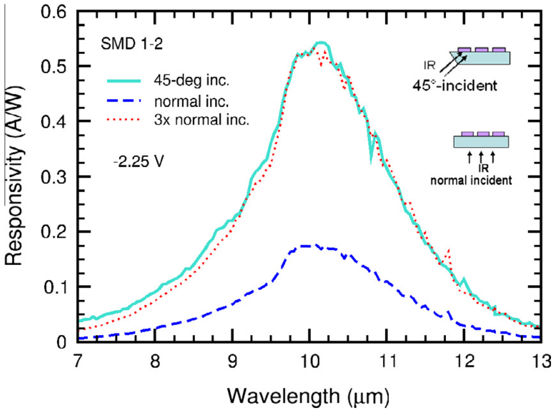

Fig. 2. Normal incidence and 45° incidence responsivity of an SML-QDIP sample. For comparison, the dotted line show the normal-incidence curve multiplied by a factor of 3. The insets illustrate the 45°-edge-coupled and normal-incidence detector geometries.

3. Unresolved issues

The original SML-QDIP work described in Ref. [1] left several unresolved issues. One is that the normal incidence response is relatively weak. In Ref. [1] we discussed some possible reasons for the relatively weak response. A likely possibility is that, because the volume of the SML QD is considerably smaller than the SK QD with the same lateral dimensions, the oscillator strength for the SML QD is also smaller. We noted that the reported devices use only two SML QD layers per quantum well, and the two QD layers are separated by a relatively large distance of ~28 Å (compare this to the dot height of ~3 Å). We suggested that by stacking more closely spaced SML QD layers, as depicted in the right panel of Fig. 3, we can increase the normal incidence absorption strength considerably.

A more serious concern was for whether the observed normal-incidence response was indeed due to 3D quantum confinement. We had cautioned [17] that other explanations, such as finite optical cavity edge effects [18], could also be responsible for the observed normal incidence response. The reason for suspecting optical scattering as being responsible for the observed normal incidence response comes from a simple argument due to Choi [19]. He points out that if two different types of transitions are involved, one sensitive to normal-incidence and the other to side-incidence radiation, then unless there is accidental (near) degeneracy, they would involve distinct transition energies. Consequently, the normal-incidence and 45° incidence response curves in Fig. 2 should have different spectral peak positions. But here we see that the spectral shapes are suspiciously similar: the 45° incidence response curve and the 3× normal incidence response curve are nearly identical. Therefore it is likely that there is only one type of (QWIP-like) transition involved in the observed response, and that the normal-incidence response is primarily the result of optical cavity scattering effect [18].

The higher normal-incidence response to 45°-incidence response ratio η_{nor}/η_{45} found in SML-QDIP was taken as evidence for intrinsic normal incidence. However, Choi et al. [18] had shown that even in a simple QWIP, where intrinsic normal incidence absorption is negligible [20], larger η_{nor}/η_{45} can be obtained in material with weaker absorption coefficient α due to the nature of the optical scattering mechanism. As illustrated in Fig. 4, the mesa etching process usually results in angled side walls, two of which are usually etched at an angle suitable favorable for reflecting normal-incidence light into the lateral propagating direction, which is compatible with QWIP absorption. Even though only a

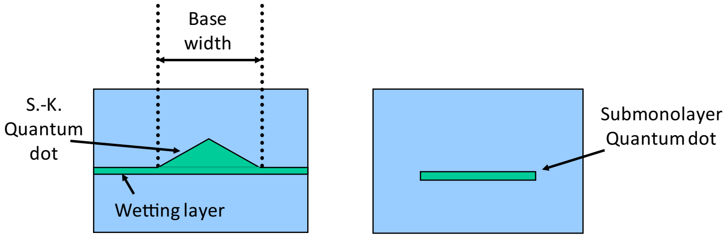

Fig. 1. The left panel illustrates a Stranski–Krastanow quantum dot, consisting of pyramidal shape quantum dot resting on a wetting layer. The right panel shows a submonolayer (SML) quantum dot.