Mid-IR integrated nanophotonics for chip-scale quantum optics applications

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ABSTRACT

An integrated nanophotonics architecture based on inter-sub-band transitions, surface depletion and plasmon mediated near field effects is reported. The combined use of these methodologies allows for the monolithic integration of passive waveguides, quantum cascade laser light sources and on-chip single photon detectors along with the precise placement of a quantum dot formed from a quantum well system for use as a single photon emitter. Such dots, when coupled to a suitable cavity, form the basis of the next generation quantum information, quantum metrology and quantum communication systems, while the overall architecture provides for a completely chip-based quantum optic functionality.

Keywords: quantum dots, integrated photonics, nanophotonics, inter-sub-band transitions, quantum wells

1 INTRODUCTION

Integrated nanophotonics at telecom wavelengths offers exciting near term opportunities in long haul, chip-to-chip and backplane communication scenarios. Even far greater opportunities exist however, when the quantum mechanical nature of the light matter interaction is considered, most significantly, at the single photon level. To enable such interactions, cavity coupled quantum dots have been suggested for use as single photon emitters and such "quantum nodes," when connected via waveguides, are considered the building blocks of the next generation of quantum information, quantum metrology and quantum communication systems [1]. That being said, imprecisions in the control of dot placement and dot size represent the most significant barriers to the development of a viable integrated quantum nanophotonic architecture for all current state-of-the-art technological approaches [2-5].

This effort reports on experiments and simulations performed on quantum well systems suggesting that through the use of inter-sub-band (ISB) transitions and surface depletion effects a quantum dot (QDot) can be reliably and precisely formed from a quantum well (QWell) system. This proposed QDot is planar in the sense that it does not require etching through the quantum well containing layers, eliminating the need for complex overgrowth or sidewall passivation schemes nor does it require a complex series of external electrodes to provide three-dimensional electron confinement.

Critical to this effort is the ability to control ISB ground state occupancy through surface depletion effects, a methodology that has been experimentally verified and reported herein. Additionally, simulations are presented establishing the feasibility of waveguide/QDot interactions mediated by the near field effects of a novel hybrid plasmon/dielectric waveguide, which, as will be shown, can also be utilized for the integration of an on-chip quantum cascade laser light source. Extensions of these ideas to form a monolithically integrated single photon detector will also be discussed. The use of these operational modes results in a completely monolithic, integrated quantum nanophotonic architecture.

2 BURIED QUANTUM DOTS

The salient characteristic of the proposed integrated architecture is the use of surface depletion effects to allow for the formation of a quantum dot system from a quantum well system. The approach is illustrated in Fig. 1 (a), which shows the schematic of an epi-layer stack including a section of quantum wells located roughly 0.26μm from the surface. Because the surface depletion width of a semiconductor is inversely proportional to the square root of the materials dopant concentration, in those regions where the highly doped cap layer is removed, the quantum well layers will reside in the surface depleted region. In those regions where the cap is in place, the wells reside outside the surface depletion region. Figure 1 (b) illustrates this via a 2-dimensional finite-element (FEM) simulation where the higher conduction band potential is clearly seen in those regions where no cap is in place. Figure 1 (c) represents a cross sectional cut through the quantum well layers of Fig. 1 (b) and illustrates the lateral electron confinement, and hence quantum dot formation, provided by this method. The location of the quantum wells to a position inside the depletion width provides lateral confinement and produces a quantum dot whose location is illustrated in Fig 1 (b). In addition, those wells that are located inside the depletion region do not have their ground state filled with electrons. This effectively allows the presence or absence of the doped cap layer to control the material's absorptive nature, a property exploited for the monolithic integration of both light sources and detectors as will be explained later.

The use of surface depletion to control ISB ground state occupancy has been demonstrated [5]. It was shown that through the use of etching, the removal of quantum well layers accompanied a reduction in the characteristic ISB

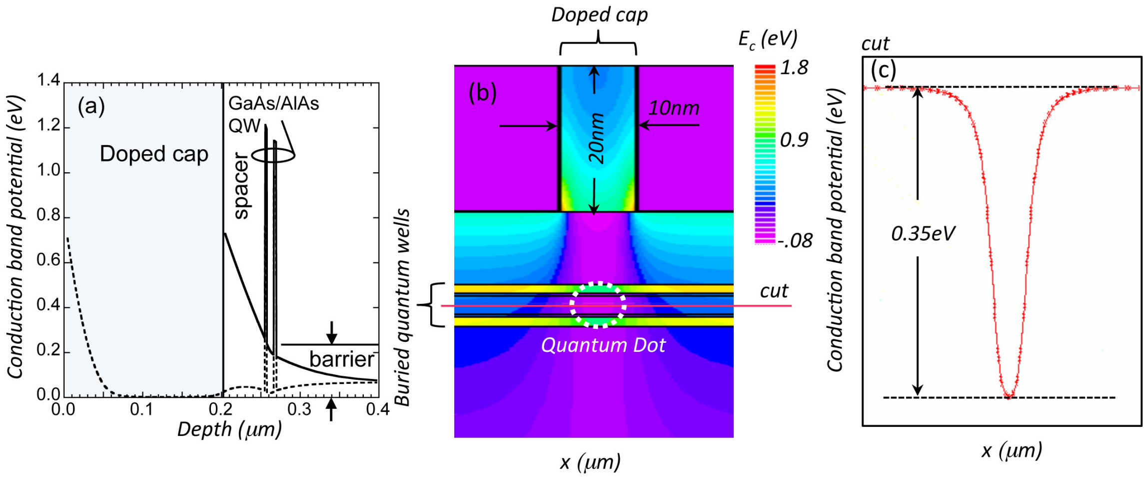

Figure 1: (a) (Dotted line) Conduction band profile with doped cap in place and (solid line) profile with doped cap removed. (b) Finite element simulation of conduction band profile used to produce (c), the cross sectional cut through the quantum wells illustrating the use of surface depletion to form a planar quantum dot from a quantum well system. The location of the buried quantum dot is shown in (b).

absorption feature as determined through Fourier transform infrared spectroscopy measurements. The etch process was halted upon the disappearance of the characteristic ISB absorption feature and high resolution transmission electron microscopy was used to confirm the presence of the remaining quantum wells, now located in the near surface region of the semiconductor. This experiment motivates the present work and suggests the use of surface depletion for use in the formation of a buried, planar, quantum dot from a quantum well system.

3 NANOPNHOTONIC ARCHITECTURE

Using the methodology described above, the QDot resides in the near surface region of the semiconductor, thus, traditional photonic waveguides will offer poor modal overlap between propagating fields and the QDots. To increase this coupling, a novel hybrid plasmon/dielectric waveguide is proposed. Figure 2 (a) shows a finite difference time domain (FDTD) simulation of this hybrid waveguide architecture and illustrates how the plasmon-related near-field effects are exploited to force all propagating modes to the near-surface region, maximizing the overlap with the near surface located QDots.

Significant to this effort is the optical wavelength range proposed. To exploit surface depletion effects, inter-sub-band transitions are required. To form a true quantum dot, with bound state energy separations similar for all optical polarization directions, the confinement width provided by the quantum well layers must be similar to the lateral confinement width provided by the doped cap layer. State of the art e-beam lithography can produce a minimum dimension of between 5nm and 10nm, while a 10nm quantum well width produces an ISB ground-to-first-excited-state transition of roughly 10μm. Thus, the integrated quantum nanophotonic architecture proposed

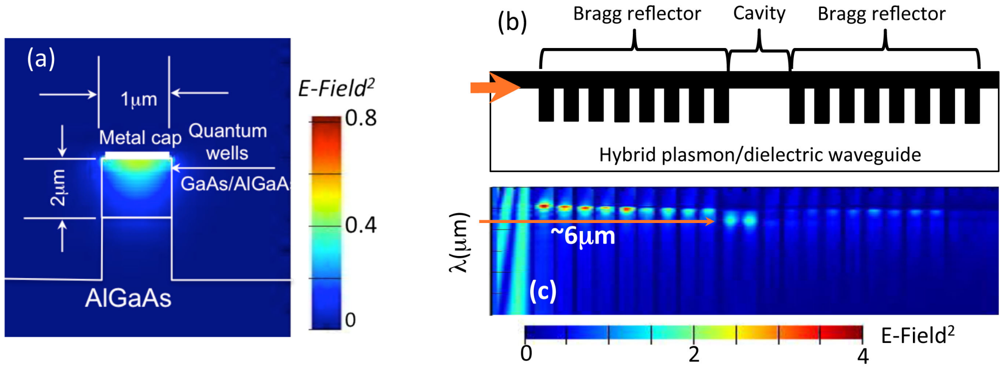

Figure 2: (a) FDTD simulation of proposed hybrid plasmon/dielectric waveguide with high near surface field intensity used to maximize interaction with near surface quantum dots. (b) Integrated QCL design incorporating plasmon Bragg grating along with plasmon/dielectric waveguide of (a). (c) FDTD simulation of non-optimized Bragg reflector showing electric field intensity enhancement in cavity.

operates in the mid-IR, a wavelength region where plasmonic effects are known to offer little loss when compared to visible and telecom wavelengths. This allows for the exploitation of plasmonic effects, not only for waveguiding purposes as described above, but also for use as small volume cavities as has been proposed by other groups for use in the implementation of cavity quantum electrodynamics at the chip-scale, albeit at shorter and hence more lossy wavelengths [7].

The nanophotonic architecture described also offers the opportunity of integrated light source as will now be described. Traditional quantum cascade lasers (QCLs) utilize inter-sub-band transitions in the generation of coherent light and typically require hundreds of periods of an appropriate epi-layer stack to function. With proper overlap between the optical mode and the QCL gain region, fabricating a single period QCL layer structure is a possibility. In addition, it is well known that the inability to cleave QCLs to the proper cavity length is the major yield failure for this technology. By utilizing the near-field effects associated with the hybrid waveguide, we can develop a plasmon-based Bragg grating. Shown schematically in Fig. 2 (b), preliminary simulations suggest that e-beam lithography, rather than mechanical cleaving, can be used to define the cavity length. Figure 2 (c) is a FDTD simulation of the non-optimized Bragg grating showing field enhancement in the cavity at an incident wavelength of roughly 6μm.The implication is that multiple cavities can now be patterned lithographically onto a single chip, and hence, multiple lasers, each emitting at a different wavelength, can be directly waveguide-coupled to the chip with virtually no loss. The concept of a plasmon-based Bragg reflector is not new, but this application in its use for the integration of a QCL directly with the nanophotonic chip represents a clear advancement in not only integrated nanophotonic technology but also in QCL light source development in general [8].

To foster inter dot communication and to provide for an on-chip light source a hybrid plasmon/dielectric waveguide with integrated Bragg reflectors has also been proposed. To complete the architecture, and to fully exploit the quantum mechanical light/mater interaction, an integrated single photon detector is also required. Historically, single photon detection at other than visible wavelengths has been problematic. It is suggested however that surface depletion effects can be utilized to develop a single photon detector simply by leaving a line of doped cap in place over the hybrid waveguide, effectively forming a quantum wire as shown in Fig. 3 (a-b). The difficulties in providing ohmic contact to the buried wire not withstanding, a dramatic change in conductance is expected to be seen when a single photon is absorbed, promoting an electron from the filled ground state to the empty first excited state where it is free to drift, under reduced electron-electron interactions, to the end contact. Further, since all functions are monolithically integrated, there will be no coupling loss and the quantum wire length is unconstrained. This means that the wire can be made of whatever length is necessary to assure absorption of any single photon, offering by definition, high quantum efficiency. If this detector is coupled with a grating responding to normal incident photons, the device becomes a stand-alone mid-IR, single photon detector. The suggestion of the use of quantum wires as single photon detectors is not without precedent [9]. It is also mentioned, that other single photon detectors not discussed here and based on quantum dots integrated with optical cavities have also been proposed [10].

The utility in allowing for the monolithic integration of light source, quantum dot and integrated detector seems apparent. Further advances in integrated quantum optics technology arise when band-gap engineering principles are applied to the underlying quantum well layers as illustrated in Fig. 4 (a-e). Figure 4 (a) illustrates an asymmetric quantum well used to produce two ground states coupled to a shared excited state, an energy manifold used to produce electromagnetically induced transparency, typically

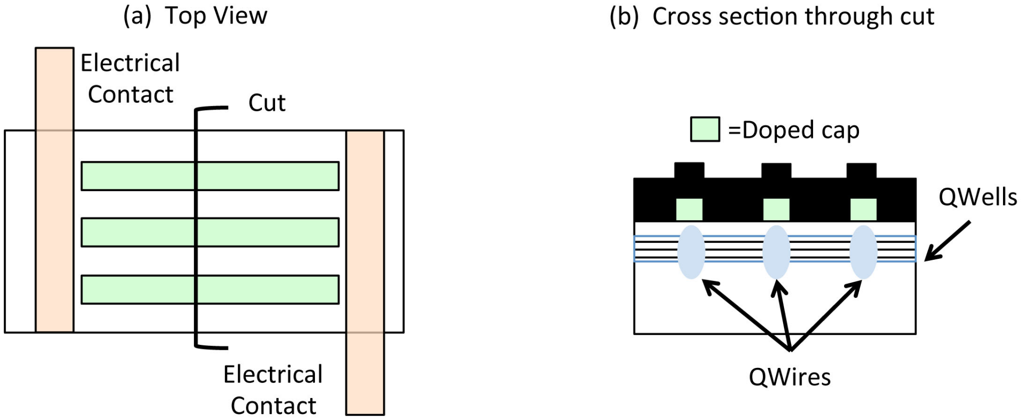

Figure 3: (a) Top view of a waveguide illustrating the formation of quantum wires for use as single photon detectors. (b) Cross section of (a) showing quantum wire formation within quantum well containing layers.

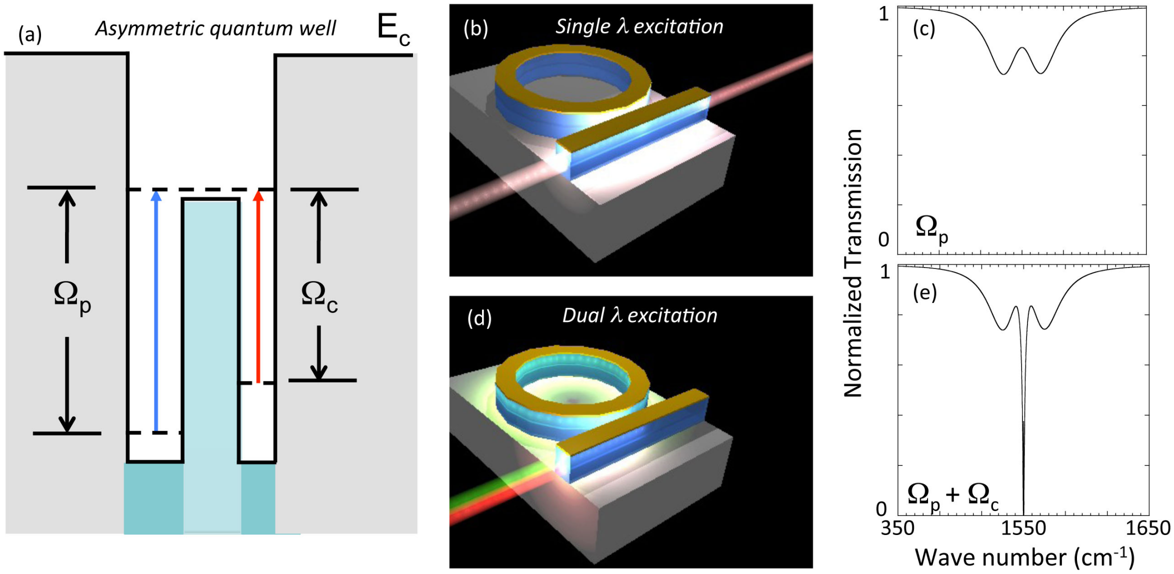

Figure 4: (a) Schematic of energy manifold associated with asymmetric QWell/QDot. (b) Rendering of such a QDot implanted in a ring resonator and (c) the response to single optical field. (d) Rendering of the same system excited by two optical fields and (d) the resultant response illustrating the electromagnetically induced transparency effect on bus waveguide transmission.

accomplished with dilute gases, but here accomplished via well established epitaxial growth techniques. Such engineered QDots, when coupled to cavities, can be used to produce a host of unique optical responses, the use of which is only beginning to be investigated. For example, Fig. 4 (b-e) shows the response of the asymmetric QDot of Fig. 4 (a), incorporated into a ring resonator producing the ability to control light with light as shown in the calculated transmission response of Figs. (c) and (e).

4 CONCLUSION

A chip-scale quantum nanophotonic architecture has been presented. Operating at mid-IR wavelengths this technology is based on inter-sub-band transitions, surface depletion effects and near field plasmonics. Such an architecture provides both on chip light source and single photon detectors as well as the potential for on-demand single photon emitters through the use of a buried QDot. It is expected that such a technology will find usefulness in quantum communication, quantum metrology and quantum information science.

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