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Fundamental Study of Antimonide Nanostructures by Molecular Beam Epitaxy (Phase II : GaSb VS InSb QDs)

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Six publications resulted from your AOARD supported project.
Following the research work on InAs quantum dots (QDs) and quantum dot molecules (QDMs) grown by molecular beam epitaxy (MBE), the research target is extended to GaSb QDs and InSb QDs on different substrates, i.e. GaAs/GaSb/InAs and Ge giving either type II or type III quantum nanostructures. This type II nanostructures would have a unique property of separated carrier confinement for novel nanoelectronic devices such as IR detectors, solar cells, memory devices, etc., and type III with tunneling effect for fast nanoelectronic devices. In phase II of the project, various physical, electrical and optical properties of these two nanostructures, i.e. GaSb and InSb, are intensively studied. The experiment is also extended to magnetic property of InSb nanostructure due to high-g factor.

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"**Fundamental Study of Antimonide Nanostructures by Molecular Beam Epitaxy**" (Phase II: GaSb VS InSB QDs)

September 2018

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Abstract:

This second annual report summarizes the results and output resulting from research activities during the past 12 months of the project supported by AOARD co-funded by ONRG from September 2017 to September 2018 conducted at Chulalongkorn University in Thailand. Following the research work on InAs quantum dots (QDs) and quantum dot molecules (QDMs) grown by molecular beam epitaxy (MBE), the research target is extended to GaSb QDs and InSb QDs on different substrates, i.e. GaAs/GaSb/InAs and Ge giving either type II or type III quantum nanostructures. This type II nanostructures would have a unique property of separated carrier confinement for novel nanoelectronic devices such as IR detectors, solar cells, memory devices, etc., and type III with tunneling effect for fast nanoelectronic devices. In phase II of the project, various physical, electrical and optical properties of these two nanostructures, i.e. GaSb and InSb, are intensively studied. The experiment is also extended to magnetic property of InSb nanostructure due to high-g factor.

Introduction:

GaSb/GaAs quantum dots are type II nanostructure. Long carrier lifetimes in type II can provide interesting electronic and optical properties. They can be applied for robust memory devices. Combined properties of both quantized and bulk features in type III leading to efficient carrier transport and high speed behavior. Optical properties of quantum nanostructures with selective photon absorption and emission can be controlled by dot morphology, dot size and dot density. GaSb/GaAs quantum dots can be a good candidate for near- and mid- infrared sensor and emitter.

Ge is a well-known bulk material for infrared sensors both intrinsic and extrinsic properties. Impurity species in doped Ge can define the spectral response from near-, mid- to far infrared wavelength. Au doped Ge is widely used for the detector of CO_2 laser at 10.6 micron wavelength. However, most of Ge detectors operate at low temperatures for better detection sensitivity.

The motivation of this research it to combine quantum nanostructures and bulk properties in nanoelectronic and nanophotonic applications. GaSb/GaAs, InSb/GaAs and Ge are selected materials for our research proposal. (001) Ge substrates are also used for quantum nanostructure preparation. Fundamental understanding of how GaAs anti-phase domains created from polar/non-polar interface giving some effects to nanostructure formation will be investigated. The photon emission from quantum nanostructures could also be defined by changing the material composition of capping and insertion layers. Photoluminescence data would be an analytical mean to understand the basic of emission phenomena from respective nanostructures.

In this proposal, the activity will be focused on InSb QDs which can be either type II (InSb/GaAs) and type III (InSb/InAs). This part of knowledge is needed to be investigated and also is our research motivation.

In the second year of research project, we also propose to extend our work on InSb nanostructure grown on GaSb substrate. InSb/GaSb nano-stripes are realized by S-K growth mode of MBE. Preliminary experimental result of InSb/GaSb is investigated and used for new research proposal submitted to AOARD for the funding in the next 2 years (2019-2020).

Raman spectroscopy of both GaSb and InSb nanostructures grown on different substrates is also studied. Raman peak shift due to magnetic field of InSb nanostructure is experimented based on its basic property of high g factor.

In addition, we work on a novel idea of using combined type I (InAs/GaAs) and type II (GaSb/GaAs) nanostructures in quantum dot solar cell structure. Interdigitated QDs with multiple stacks are realized and studied for its improved solar cell performance.

Experiment:

GaSb/GaAs and InSb/GaAs quantum nanostructures are grown by molecular beam epitaxy using S-K and droplet epitaxy methods. S-K growth mode is a strain-driven process due to lattice mismatches between GaSb and GaAs (7.2 %) and between InSb and GaAs (14.6 %). However, this approach has some drawback due to residual strain occurred during high growth temperature. Droplet epitaxy method is a lower temperature growth process. We have developed a novel MBE growth technique using low growth temperature (250-300˚c) and low growth rate (0.01-0.02 ML/s) to realize high quality Antimony (Sb) based nanostructures.

Results and Discussion:

GaSb QDs are experimentally grown on GaAs and Ge substrates. Photoluminescence (PL) measurement is also conducted to study their optical property reflecting their dot size, dot density and dot uniformity which are basic information for future device design, especially detector applications in the near infrared region. Multi-stacked GaSb QDs are also prepared for better detectivity of the devices. With control of III-V ratio during MBE growth GaSb QDs are elongated within each GaAs anti-phase domain (APD) leading to polarization dependence PL.

InSb QD is another quantum nanostructure grown by MBE. InSb is the narrowest bandgap semiconductor and is useful for it is capable of longer infrared wavelength detection comparing to GaSb.

In addition, InSb has the highest electron mobility (78,000 cm^2/V-Sec). Therefore, InSb QDs are useful for high speed nanoelectronic applications. Another unique property of InSb is very small electron effective mass providing a high g-factor of 50. This leads to a very interesting application of InSb for magnetic field sensing. We conduct a Raman spectroscopy experiment on InSb nanostructure under applied magnetic field to observe Raman shift at various values of magnetic field strength.

Interdigitated QDs between type I (InAs/GaAs) and type II (GaSb/GaAs) QDs are grown by MBE technique. Photoluminescente result of this interdigitated structure shows photon absorption and photon emission from type I QDs and subsequent photon re-absorption by type II QDs to provide better short-circuit current of the solar cell. (Details of all experimental results and discussions are found in published papers listed below).

List of Publications and Significant Collaborations that resulted from your AOARD supported project: In standard format showing authors, title, journal, issue, pages, and date, for each category list the following:

a) papers published in peer-reviewed journals,

- a1) "Toward Quantum State Manipulation in Twin InSb/GaAs Quantum Dots", Suwit Kiravittaya, Supachok Thainoi, Zon Somchai Ratanathammaphan, Songphol Kanjanachuchai, Somsak Panyakeow, Journal of IEEE, (Manuscript), 978-1-5090-4666-9/17, 2017.
- a2) "Twin InSn/GaAs Quantum Nano-Stripes: Growth Optimization and Related Properties", Phisut Narabadeesuphakorn, Supachok Thainoi, Aniwat Tandaechanurat, Suwit Kiravittaya, Noppadon Nuntawong, Suwat Sopitpan, Visittapong Yordsri, Chanchana Thanachayanont, Songphol Kanjanachuchai, Somchai Ratanathammaphan, and Somsak Panyakeow, Journal of Crystal Growth, 487, pp. 40-44, 2018.
- a3) "Preferential Nucleation, Guiding and blocking of Self-Propelled Droplets by Dislocations", Songphol Kanjanachuchai, Thipusa Wongpinij, Suphakan Kijamnajsuk, Chalermchai Himwas, Somsak Panyakeow, Pat Photongkam, Journal of Applied Physics 123, 161570-1-161570-11, 2018.
- a4) "Growth and Photoluminescence Properties of InSb/GaSb Nono-Stripes Grown by Molecular Beam Epitaxy", Supeeranat Posri, Supachok Thainoi, Suwit Kiravittaya, Aniwat Tandaechanurat, Noppadon Nuntawong, Suwat Sopitpan, Visittapong Yordsri, Chanchana Thanachayanont, Songphol Kanjanachuchai, Somchai Ratanathammaphan, and Somsak Panyakeow, (Submitted to Journal of Physica Status Solidi).

a5) “Growth-Rate-Dependent Properties of GaSb/GaAs Quantum Dots on (001) Ge Substrate by Molecular Beam Epitaxy”, Zon, Pakawat Phienlumlert, Supachok Thainoi, Suwit Kiravittaya, Aniwat Tandaechanurat, Noppadon Nuntawong, Suwat Sopitpan, Visittapong Yordsri, Chanchana Thanachayanont, Songphol Kanjanachuchai, Somchai Ratanathammaphan, Somsak Panyakeow, Yasutomo Ota, Satoshi Iwamoto and Yasuhiko Arakawa, (Submitted to Journal of Physica Status Solidi).

a6) “Demonstration of Photovoltaic Effects in Hybrid Type-I InAs/GaAs Quantum Dots and Type-II GaSb/GaAs Quantum Dots”, Thanaphat Rakpaises, Nanthaphop Sridumrongsak, Chanyanuch Chevintulak, Supachok Thainoi, Suwit Kiravittaya, Noppadon Nuntawong, Suwat Sopitpan, Songphol Kanjanachuchai, Somchai Ratanathammaphan, Aniwat Tandaechanurat, and Somsak Panyakeow, (Submitted to WCPEC Proceeding- Journal of IEEE Photovoltaics)

b) papers published in peer-reviewed conference proceedings,

b1) “Measurement of Current-Voltage (I-V) Characteristics of Ga Droplets on GaAs Surface”, Beni Adi Trisna, Jadtasit Leelasumphanlert, Somsak Panyakeow, and Songphol Kanjanachuchai, 1st International Conference on Metrology (Iconmet 2017), Jakarta, Indonesia on 25-26 October, 2017.

b2) “Growth and Photoluminescence Properties of InSb/GaSb Nono-Stripes Grown by Molecular Beam Epitaxy”, Supeeranat Posri, Supachok Thainoi, Suwit Kiravittaya, Aniwat Tandaechanurat, Noppadon Nuntawong, Suwat Sopitpan, Visittapong Yordsri, Chanchana Thanachayanont, Songphol Kanjanachuchai, Somchai Ratanathammaphan, and Somsak Panyakeow, Compound Semiconductor Week (CSW-2018), Massachusetts Institute of Technology (MIT), Cambridge Boston, USA, pp. 151, 29 May-1 June, 2018.

b3) “Unique Polarization-Dependent Photoluminescence Property of GaSb/GaAs Quantum Dots on (001) Ge Substrate Grown By Molecular Beam Epitaxy”, Zon, Pakawat Phienlumlert, Supachok Thainoi, Suwit Kiravittaya, Aniwat Tandaechanurat, Noppadon Nuntawong, Suwat Sopitpan, Visittapong Yordsri, Chanchana Thanachayanont, Songphol Kanjanachuchai, Somchai Ratanathammaphan, Somsak Panyakeow, Yasutomo Ota, Satoshi Iwamoto, and Yasuhiko Arakawa, Compound Semiconductor Week (CSW-2018), Massachusetts Institute of Technology (MIT), Cambridge Boston, USA, pp. 192, 29 May-1 June, 2018.

b4) “Demonstration of Photovoltaic Effects in Hybrid Type-I InAs/GaAs Quantum Dots and Type-II GaSb/GaAs Quantum Dots”, Thanaphat Rakpaises, Nanthaphop Sridumrongsak, Chanyanuch Chevintulak, Supachok Thainoi, Suwit Kiravittaya, Noppadon Nuntawong, Suwat Sopitpan, Songphol Kanjanachuchai, Somchai Ratanathammaphan, Aniwat Tandaechanurat, and Somsak Panyakeow, 7th World Conference on Photovoltaic Energy Conversion (IEEE-PVSC-45, EU PVSEC-34, PVSEC-28), Waikoloa, Hawaii, USA, 10-15 June 2018.

b5) “Study on Raman Spectroscopy of InSb Nano-Stripes Grown on GaSb Substrate by Molecular Beam Epitaxy and Their Raman Peak Shift with Magnetic Field”, Putita Lekwongderm, Rujtira Chumkaew, Supachok Thainoi, Suwit Kiravittaya, Aniwat Tandaechanurat, Noppadon Nuntawong, Suwat Sopitpan, Visittapong Yordsri, Chanchana Thanachayanont, Songphol Kanjanachuchai, Somchai Ratanathammaphan, and Somsak Panyakeow, 20th International Conference on Molecular Beam Epitaxy (MBE-2018), Shanghai, China, 2-7 September, 2018.

b6) “Effects of Magnetic Field on Raman Scattering of InSb/GaAs Quantum Nanostructures”, E. Rattanawongnara, Supachok Thainoi, Suwit Kiravittaya, Aniwat Tandaechanurat, Noppadon Nuntawong, Suwat Sopitpan, Visittapong Yordsri, Chanchana Thanachayanont, Songphol Kanjanachuchai, Somchai Ratanathammaphan, and Somsak Panyakeow, 20th International Conference on Molecular Beam Epitaxy (MBE-2018), Shanghai, China, 2-7 September, 2018.

b7) “Anti-Phase Domain Induced Morphological Differences of Self-Assembled InSb/GaAs Quantum Dots Grown on Ge Substrate”, Zon, Supachok Thainoi, Suwit Kiravittaya, Aniwat Tandaechanurat, Noppadon Nuntawong, Suwat Sopitpan, Visittapong Yordsri, Chanchana Thanachayanont, Songphol Kanjanachuchai, Somchai Ratanathammaphan, and Somsak Panyakeow, 20th International Conference on Molecular Beam Epitaxy (MBE-2018), Shanghai, China, 2-7 September, 2018.

b8) “Molecular Beam Epitaxial Growth of Interdigitated Quantum Dots and Their Potential Application to Heterojunction Solar Cells”, Chanyanuch Chevuntulak, Thanaphat Rakpaises, Nanthaphop Sridumrongsak, Supachok Thainoi, Aniwat Tandaechanurat, Suwit Kiravittaya, Noppadon Nuntawong, Suwat Sopitpan, Visittapong Yordsri, Chanchana Thanachayanont, Songphol Kanjanachuchai, Somchai Ratanathammaphan, and Somsak Panyakeow, 20th International Conference on Molecular Beam Epitaxy (MBE-2018), Shanghai, China, 2-7 September, 2018.

b9) “InSb/InAs Quantum Nano-Stripes Grown by Molecular Beam Epitaxy and its Photoluminescence at Mid-Infrared Wavelength”, Ratthapong Khanchaitham, Panithan Srisinsuphya, Karn

Rongrueangkul, Supachok Thainoi, Aniwat Tandaechanurat, Suwit Kiravittaya, Noppadon Nuntawong, Suwat Sopitpan, Visittapong Yordsri, Chanchana Thanachayanont, Songphol Kanjanachuchai, Somchai Ratanathammaphan, and Somsak Panyakeow, 20th International Conference on Molecular Beam Epitaxy (MBE-2018), Shanghai, China, 2-7 September, 2018.

c) papers published in non-peer-reviewed journals and conference proceedings,

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d) conference presentations without papers,

d1) "Semiconductor Quantum Nanostructure for Metrology", (Invited Talk), Somsak Panyakeow, 1st International Conference on Metrology (Iconmet 2017), Jakarta, Indonesia on 25-26 October, 2017.

d2) "Introduction of Quantum Device Research Activity at SDRl, Chulalongkorn University", (Invited Talk), Somsak Panyakeow, Gajarmada University, Yogyarkata, Indonesia, 27 October, 2017.

e) manuscripts submitted but not yet published,

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f) provide a list any interactions with industry or with Air Force Research Laboratory scientists or significant collaborations that resulted from this work.

Discussion with researchers from Naval Research Laboratory (Dr. Allan Bracker and his colleague) during CSW-2017 at MIT, Boston, 29 May-2 June, 2018.

Attachments: Publications a), b) and c) listed above if possible.

DD882: As a separate document, please complete and sign the inventions disclosure form.

Important Note: If the work has been adequately described in refereed publications, submit an abstract as described above and refer the reader to your above List of Publications for details. If a full report (e.g. for any unpublished work) needs to be written, then submission of a final report that is very similar to a full length journal article will be sufficient in most cases. This document may be as long or as short as needed to give a fair account of the work performed during the period of performance. There will be variations depending on the scope of the work. As such, there is no length or formatting constraints for the final report. Keep in mind the amount of funding you received relative to the amount of effort you put into the report. For example, do not submit a $300k report for $50k worth of funding; likewise, do not submit a $50k report for $300k worth of funding. Include as many charts and figures as required to explain the work.