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...RT DATE: ...18/1991

3. REPORT TYPE AND DATES COVERED: Annual Technical 12/15/90 to 12/14/91

4. TITLE AND SUBTITLE

Pseudomorphic narrow gap materials for high performance devices

5. FUNDING NUMBERS

PE 61153N
R&T# 414S006
ONR N0014-90-J-1536

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9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
800 N. Quincy Street, Arlington, VA 22217

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

InAs field effect transistors (1 μm gate length) have been fabricated and showed extrinsic (intrinsic) transconductance as high as 414 mS/mm (670mS/mm). The cut-off frequency is estimated to be more than a factor of two greater than is typical for GaAs based FET's with comparable gate length. The FET has also been operated at electric fields greater than 20 kV/cm without any indication of breakdown, far above the bulk breakdown value of 6 kV/cm. Several mechanisms have been proposed to explain this phenomenon. The threshold current densities of separate confinement strained AlGaAs/GaAs/InGaAs lasers have been shown to be insensitive to the quality of the AlGaAs outer cladding layers due to the use of a thick GaAs inner cladding layer. We have also shown theoretically that (1) infrared absorption at normal incidence due to intervalence subband transition can be greatly enhanced in light hole and heavy-hole inverted strained GaInAs/AlInAs quantum wells, and (2) with biaxial tensile strain, exciton absorption and saturation limit in quantum wells can be be enhanced.

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

Accession For
NTIS GRA&I ☒
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A-1

OFFICE OF NAVAL RESEARCH

Annual Technical Report

FOR

15 December 1990 through 14 December 1991

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CONTRACT: N00014-90-J-1536

R&T NO: 414 s 006

TITLE OF CONTRACT: Pseudomorphic Narrow Gap Materials for High Performance Devices

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In the past year, several strained-layer electronic and optical devices have been conceived and developed. The achievements are summarized in the following:

Normal incidence infrared photoabsorption in p-type GaSb/GaAlSb quantum wells

We have investigated infrared absorption properties at normal incidence in p-type GaSb/$Ga_{1-x}Al_xSb$ quantum wells. Normal incidence absorption is intrinsically allowed in conventional p-type quantum wells due to the favorable properties of the p-like valence-band Bloch states and the light-hole and heavy-hole mixing. Unlike s-like conduction-band Bloch states (|s>) for electrons, the Bloch states for holes are linear combinations of p-like valence-band Bloch states (|x>, |y>, and |z>), which can provide nonzero coupling to normally incident radiation. The strong heavy-hole and light-hole mixing due to the QW potential further promotes absorption at normal incidence. An advantage of this detection scheme is that it allows the use of wide- and direct-gap semiconductors. However, the inter-valence subband absorption in conventional p-type quantum wells, such as in p-type GaAs/$Ga_{1-x}Al_xAs$, is too small to be useful for photodetection applications. This is because in conventional p-type quantum wells free holes occur primarily in the heavy-hole ground state with large effective masses. Therefore weak absorption results from the inverse relationship between the effective mass of free carriers and the absorption coefficient. Taking into account the fact that smaller effective mass corresponds to stronger absorption, we choose a well material with a relatively small heavy-hole effective mass, GaSb, in order to strengthen the absorption. Among the widely used III-V semiconductors, GaSb has the smallest heavy-hole effective mass ($m^*_{hh}/m_0 = 0.26$, m_0 is the free electron mass), which is about half the heavy-hole mass of GaAs ($m^*_{hh}/m_0 = 0.45$). Previously, we have taken advantage of this feature and fabricated p-channel GaSb field-effect transistors which exhibited the highest transconductance reported for any III-V compound p-channel field-effect transistors. Here, we found that normal incidence absorption of $3000\text{-}6000\ cm^{-1}$ can be easily achieved in these proposed quantum wells with well widths of $55\text{-}90\ \AA$ for the wavelength range of $8\text{-}12\ \mu m$ and typical sheet doping concentrations of $10^{12}\ cm^{-2}$. This absorption strength is an order of magnitude larger than that in p-type GaAs/$Ga_{1-x}Al_xAs$ and comparable to that in the intrinsic $Hg_{1-x}Cd_xTe$ detector. Strong absorption of normally incident radiation makes this structure a good candidate for infrared photodetection.

Infrared absorption enhancement in light-hole and heavy-hole inverted strained GaInAs/AlInAs quantum wells

We have studied an alternative approach to improve the inter-valence subband absorption in p-type quantum wells. Absorption at normal incidence is found to be significantly enhanced in $Ga_{1-x}In_xAs/Al_{1-y}In_yAs$ quantum wells with light-hole and heavy-hole inversion. The inversion can be achieved with the effects of biaxial tensile strain in the quantum well due to the lattice mismatch between the well material and substrate. In this way p-type quantum well infrared detectors can be designed such that the light-hole state becomes the ground state for free holes with small effective masses, thereby producing stronger absorption. We found that in this light-hole and heavy-hole inverted structure with a well width of 60 Å, the infrared absorption can be greatly enhanced up to $8500\ cm^{-1}$ for normally incident radiation of $12\ \mu m$, which is comparable to that in the intrinsic $Hg_{1-x}Cd_xTe$ detector. This novel structure's ability to detect normally incident radiation makes it promising for infrared photodetection applications.

Enhanced Exciton Absorption and Saturation Limit in Strained InGaAs/InP Quantum Wells

The discovery of the room temperature Stark shift of the exciton-absorption peaks in quantum wells (QW's) has made possible novel devices, such as MQW self-electro-optical effect devices (SEED's) and electro-optic modulators. SEED's have since become the key devices used in optical switching and optical computing. MQW modulators, which overcome the deficiencies associated with directly modulated semiconductor lasers, are excellent candidates for use in high speed communication transmitters.

In order to improve device performance, extensive research has been focused on increasing the exciton-absorption peak value and the saturation limit. We propose a new approach to raising these parameters, using MQW's in which the well layer is under tensile strain.

When tensile strain is applied to the QW, the effective mass of the top valence band can increase and change sign (corresponding to a change in the in-plane valence band structure). As the valence band effective mass is increased the effective mass of a direct exciton, formed by an electron from the conduction band coupling to a hole from the top valence band, can be drastically increased. An increase in exciton mass leads to a reduction of exciton radius (greater overlap of electron and hole), and therefore an increase in exciton-absorption peak. Furthermore, the increase in exciton mass and the change in the sign of the hole mass lead to reduced saturation effect -- an increase in saturation intensity. The major saturation mechanism is due to the band-filling effect (Pauli-exclusion effect). The saturation intensity is inversely proportional to the exciton lifetime because the shorter the lifetime the faster an optically created exciton disappears from the filled state. Changing the in-plane valence band structure can reduce the exciton lifetime by several orders of magnitude, thereby allowing higher intensities of light to be absorbed. With the effects of strain in MQW's, opto-electronic devices can be designed to achieve larger exciton-absorption and higher saturation intensity than currently available.

High Breakdown Voltage InAs Channel Field-Effect Transistors

In InAs, the high electron mobility allows carriers to gain velocity quickly, while the large satellite valley spacing should yield higher carrier transient and steady-state velocities than both InP and GaAs. As a result, both long and short channel InAs channel FET's should outperform InP and GaAs based devices. However, because of the narrow bandgap of InAs (0.36 eV) it has been predicted that breakdown due to impact ionization will severely limit device performance. In bulk InAs, it has been predicted that the threshold for breakdown due to impact ionization should be on the order of 6 kV/cm. To date these results have been supported by the fact that all InAs channel FET's have exhibited behavior indicative of breakdown at drain-to-source voltages near 1 V. In this paper we demonstrated the room temperature operation of an AlSbAs/InAs heterostructure FET (HFET) that operates at channel electric fields (20 kV/cm) several times higher than the predicted threshold for impact ionization. Maximum drain current densities of 450 mA/mm were measured and operation at a drain voltage (V_{ds}) as high as 2.2 V was observed without any indication of channel breakdown. In addition, transconductances as high as 414 mS/mm and output conductances as low as 33 mS/mm are also observed at room temperature, yielding voltages gains on the order of 10. Based upon a calculated source resistance (0.94 W-mm), the intrinsic transconductance was determined to be 670 mS/mm. From this transconductance, the cut-off frequency of the device can be estimated to be 39 GHz which is more than a factor of two greater than is typical for GaAs based FET's of comparable gate length (16 GHz). Also, since carrier velocities are not expected to saturate in InAs, a constant-mobility model is used to project cut-off frequencies in the 600 GHz range for 0.25 μm gate InAs FET's.

In addtion, several mechanisms for the breakdown enhancement have been proposed by us. In general these mechanisms depend on the different vertical and horizontal structure of the FET as compared to a bulk InAs sample. Nonetheless, whatever the reason, our results do demonstrate that bulk breakdown values do not define the limit for operation of InAs channel FET's, establishing that InAs FET's may operate at higher supply voltages than previously considered possible.

AlGaAs-GaAs-InGaAs strained laser structure with performance insensitive to AlGaAs layer quality

It has been established from deep level transient spectroscopy (DLTS) and SIMS experiments that AlGaAs grown by MBE (and possibly MOCVD as well) always contains defects and impurities due to the incorporation of oxygen during crystal growth. These defects form traps in the AlGaAs wide-bandgap regions which serve as sources of non-radiative recombination that increase laser threshold and reduce the reliability of the device. The density of these defects can be minimized by performing AlGaAs MBE growth around 700 °C, however at this high growth temperature precise control of the GaAs thickness and Al composition is difficult to achieve due to the re-evaporation of Ga from the growing surface. We have studied and demonstrated a step separate confinement strained single quantum well laser that exhibits state-of-the-art threshold current densities which are insensitive to AlGaAs layer quality. The insensitivity of the threshold current density to AlGaAs quality is attributed to the use of a large GaAs region (~120 nm) outside the InGaAs quantum well. This large GaAs region reduces the influence of traps in the AlGaAs layer on the active region of the device. Laser structures with AlGaAs layers grown at different substrate temperatures (580 °C to 700 °C) exhibit similar threshold current densities while photoluminescence measurements on the AlGaAs layers of these samples exhibit large variations in the peak intensity. Thus large variations in the quality of the AlGaAs layers in our structure have little effect on the active region of the device. Our strained layer laser structure is useful for consistently producing low threshold lasers for experimental purposes and potentially offers improved reliability and manufacturability over GRIN-SCH structures due to the removal of non-radiative and dark line defect producing sites from the active region of the device. Conceivably, our structure can also be applied to other strained-structures with Al-containing compounds, such as InAlAs/$In_xGa_{1-x}As$/$In_yGa_{1-y}As$ (y<x) and InAlP/$In_xGa_{1-x}P$/$In_yGa_{1-y}P$ (y<x).

At present, a single InGaAs strained quantum well sandwiched between graded AlGaAs cladding layers, i.e. GRIN-SCH structure (graded-index separate confinement heterostructure), is the most commonly used strained laser structure. Although it has better carrier confinement than our structure, it is a difficult task to routinely produce the precisely graded and low defect density AlGaAs layers necessary for these GRIN-SCH structures.

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PATENTS FILED

none

GRADUATE STUDENTS WORKING UNDER CONTRACT FOR YEAR ENDING 14 December 1991

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