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Kink-free AlInAs/GaInAs/InP modulation-doped field effect transistors from materials grown under normal molecular beam epitaxy conditions and high transconductance P-channel GaSb MODFET with very low gate leakage currents for complementary circuit applications have been developed. A hot electron bipolar transistor (Auger transistor) has been studied theoretically to show that a substantial improvement over conventional HBTs due to the reduced base resistance. We have also demonstrated theoretically that dominant Auger process in InGaSb/AlGaSb strained quantum well structures can be suppressed.

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In the past year, various electronic and optical devices have been developed and studied under this program. The achievements are summarized below:

P-Channel GaSb MODFET for Complementary Circuit Applications

We reported the successful operation of the first AlSbAs/GaSb p-channel MODFET. The AlSbAs/GaSb MODFET offers several advantages over AlGaAs/GaAs p-channel HFET structures. The hole mobility of GaSb of 850 cm^2/Vs at 300K is one of the highest in III-V compounds and is more than twice that of GaAs. In addition, a substantial valence band offset exists between AlSb and GaSb resulting in reduced gate leakage currents.For 1μm gate length devices, transconductances of 50 mS/mm at room temperature and as high as 283 mS/mm at 77K were measured. This is the highest transconductance achieved for any p-channel compound FET with comparable geometry. We attribute this excellent performance to the superior transport properties of holes in GaSb. The devices exhibited gate leakage currents, measured at 77K, three orders of magnitude lower than the maximum drain saturation current. This low leakage current is due to the large valence band offsets in this material system. Thus an optimized p-channel device could be integrated with an AlSb/InAs n-channel HFET to lead to high performance complementary circuits.

As aforementioned, such p-channel devices can be integrated with our previously reported AlGaSb/InAs n-channel HFET to form a complementary circuit technology that is predicted to have a significant performance advantage over AlGaAs/GaAs C-HFET structures. The superior transport properties of electrons in InAs and holes in GaSb and their corresponding band offsets to AlSb or AlSbAs yield devices with transconductances much higher than AlGaAs/GaAs n- and p-channel HFETs. Consequently, we showed that a complementary circuit fabricated from these devices could provide room temperature performance with an ultimate gate delay six times shorter than that predicted for the AlGaAs/GaAs complementary circuits.

Kink-Free AlInAs/GaInAs/InP HEMTs

Lattice matched AlInAs/GaInAs/InP high electron mobility transistors (HEMTs) have demonstrated excellent DC and microwave performance. However, a peak in the DC output conductance plot, known as the "kink" effect, makes these structures undesirable for low noise and digital applications. A reduction in this kink effect has been attributed to a high quality AlInAs buffer layer. However elimination of this effect is more complicated. We have successfully fabricated kink-free AlInAs/GaInAs/InP HEMT's which were grown under normal MBE growth conditions.

The AlInAs buffer layer was grown with V:III flux ratio of 10. A very low lattice mismatch between the AlInAs buffer layer and the InP substrate of less than 3×10^{-4}, measured by a five crystal xray diffractometer, was achieved. Hall measurments show electron mobilities of 7500 cm^2/Vs at room temperature and 30,000 cm^2/Vs at 77K. The 1μm gate-length devices fabricated with this structure exhibited a maximum extrinsic transconductance of 450 mS/mm and a maximum current density of 600 mA/mm. These results represent the best reported for this material system and device size to date. The drain I-V characteristics show no kink within the range of V_{GS} varying from 0.4V to -1.2V and V_{DS} varying from 0V to 2V. The DC output conductance exhibited no kink effect with V_{GS} varying from 0.3V to 0.9V and V_{DS} varying from 0V to 2V. The output conductance at the peak transconductance was found to be 35 mS/mm. We believe the elimination of the kink effect can be attributed to our high quality AlInAs buffer layer and the excellent lattice matching, both of which were achieved under normal MBE growth conditions.

Analytic Theory of the Hot Electron Bipolar (Auger) Transistor

We investigated the potential and possibility of a hot electron bipolar (Auger) transistor by deriving an analytic theory, and then applied this analytic theory to investigate the performance of such a transistor in plausible material systems. We have included the effect of parasitics in this simple theory to project the figures of merit for high frequency applications. We investigated the single electron-hole pair generation dominated limit using material parameterization, and compared it with behavior of the same device in the absence of Auger generation.

The Auger transistor is a heterojunction bipolar transistor that utilizes impact ionization caused by injected hot carriers to generate electron-hole pairs. The Auger generation processes are similar to the impact ionization processes of the p-n junction except that the excess kinetic energy occurs through the potential step of injection instead of drift in an electric fields as in the p-n junction impact ionization. The Auger transistor is unique among hot carrier devices in that it does not need a large mean free path for successful operation. It also does not need the very short basewidth required in hot carrier unipolar transistors. Auger processes also become stronger with a decrease of the bandgap and increase of the injected hot carrier energy.

Our analysis suggests that Auger transistors, employing very small bandgap semiconductors in the heavily doped base and operating at low temperatures, will exhibit appealing performance as devices are scaled in size and operating voltage. We found that the net base resistance is reduced because of the impact ionization process contributes a negative differential resistance. Excess holes are collected at the base ohmic contact, producing a base current which flows out of the device terminal, opposite to the usual npn base current. Due to this reduced base resistance, a substantial increase in f_{max} of 45% is possible compared to a conventional HBT counterpart. Consequently, we concluded that the device is a suitable candidate for microwave power generation at high frequencies.

Reduction of Non-Radiative Auger Recombination in Long Wavelength Quantum Well Lasers

A major factor limiting the performance of long-wavelength semiconductor lasers is carrier loss due to Auger recombination. Band to band Auger recombination in InGaAsP and InGaSb bulk and quantum well structures are dominated by the CHHS process where an electron (C) recombines with a heavy hole (H) and excites a heavy hole (H) to a split-off band (S). In a strained quantum well, the in-plane heavy hole effective mass is reduced due to heavy and light hole band mixing. This reduction has been shown to reduce the threshold current and effectively increase the modulation speed in strained quantum well lasers.

We investigated the effect of the heavy hole effective mass on the Auger recombination process and derived an analytic expression for the in-plane heavy and light hole masses in a strained quantum well. We showed for the first time that the dominant CHHS Auger recombination process in InGaSb/AlGaSb strained quantum well structures can be suppressed because of the small in-plane heavy hole effective masses. Consequently, low threshold and good temperature performance can be achieved in strained quantum well lasers. Calculations show that this suppression can occur both in InGaSb/AlGaSb and InGaAsP/InP strained quantum well structures. We concluded therefore that for laser structures operating in the infrared region, a strained structure will perform better than a lattice-matched structure.

Modeling of Split-Gate and Dual-Gate InAs FETs

The superior electron transport properties of InAs and its staggered band alignment with AlGaSb can lead to FETs with an order of magnitude higher transconductance compared to existing devices based on the AlGaAs/GaAs material system. Split-gate and dual-gate FET structures offer performance advantages over a conventional single gate design, including increased transconductance. The larger transconductance is due in part to the high drift velocity in InAs which can be more fully exploited using a split-gate design. To quantify the benefits of the split-gate device, modeling calculations were performed comparing a dual-gate design to a single gate design. The results, shown in Figure 4, show that the maximum transconductance is achieved at a much smaller gate voltage swing compared to the single gate device. This smaller required gate voltage swing is advantageous for the InAs device since higher output currents can be obtained for lower voltage swings. The resulting reduced gate to source and drain to source voltages will aid in minimizing the gate-leakage current and impact ionization of carriers that can occur in the narrow band-gap InAs channel.

The advantages of a dual-gate device are the increased function and greater gain that the second gate provides. This enhanced gain is especially important for InAs devices which so far have exhibited a relatively large output conductance. In AlGaAs/GaAs the trade-off is a faster roll-off of the gain with frequency in a dual-gate design than with the single gate design. Due to the lack of negative differential mobility in the velocity-field curves of InAs, this trade-off does not exist. Therefore, the electrons will maintain their velocity after passing through the first gate. The frequency response then, should more closely resemble that of a single gate device. Using a small signal model to analyze the dual-gate device, we showed that the transconductance of the dual-gate device will be almost that of a single gate devices. It was also shown that the output resistance of the dual-gate FET is much greater than a single gate device. Therefore the output gain of the dual-gate device is greater than that of the single gate device. Furthermore, we predicted the gain of the dual-gate device to be greater than the single gate device at low frequencies. We also predicted the overall gain of the dual-gate AlGaSb/InAs HFET could be up to 40 db greater than that for similar AlGaAs/GaAs devices.

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