Interdigital-Gated HEMT Structure for High Frequency Devices

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Abstract – Interdigital-gated AlGaAs/GaAs high electron mobility transistor (HEMT) structure was used to investigate the interaction between the drifting carrier plasma waves and electromagnetic (EM) waves. It was shown theoretically that the interaction in the range from microwave to terahertz (THz) at room temperature should produce negative conductance characteristics when the carrier drift velocity slightly exceeds the phase velocity of EM waves. S-parameter reflection measurements were carried out at room temperature for a frequency range from 1 to 20 GHz and a drastic change in conductance was observed at 5GHz and 10GHz with the increase of drain-source voltage. Large conductance change over 1000 mS/mm was obtained and it showed a peak at a certain frequency. The peak position could be controlled by changing the pitch size of the interdigital gates. These characteristics can be used for high frequency applications such as high-speed switching devices although a feature size of our interdigital-gated HEMT device is much larger than conventional HEMT device.

Keywords: Plasma wave, HEMT, Interdigital, Negative conductance, Terahertz

1. Introduction

Being motivated by the tremendous success of traveling wave tubes (TWTs), the possibilities of obtaining an extremely large amplification of electromagnetic (EM) waves by utilizing a coupling between drifting carriers in semiconductor and EM waves propagating in slow-wave circuits were theoretically explored [1]. Some innovative experimental work was also carried out to realize a solid-state traveling wave amplifier (SSTWA) [2]. All of this work was done in the 1960s and 1970s when semiconductor technology was still poor. These activities faded out without remarkable success mainly due to the strongly collision dominant nature of semiconductor plasma as compared with electrons traveling in vacuum.

Due to significant progress in semiconductor material and device fabrication technologies, frequencies handled by conventional semiconductor devices have been remarkably enhanced, approaching terahertz (THz) frequencies where transit time limitation of those devices now imposes very severe limitations on the frequency and power capabilities of devices. In fact, the maximum cut-off frequency, f_T, obtained thus far in conventional devices still remains slightly above 500GHz, even with the use of short gate lengths of a few tens of nanometer (nm) and gate channel distances of a few nm [3]. In addition, it is also known that such transit time devices with reduced gate lengths show severe short-channel effects and large gate leakage currents. Thus, it is unlikely that such conventional devices will really achieve operation in the THz region with acceptable performance.

Recently, the use of plasma waves for wave detection in THz region at low temperature supported by a non-drifting 2DEG with an AlGaAs/GaAs heterostructure under a metal gate which was proposed by Dyakonov and Shur [4] have been successfully demonstrated. There is also a stimulating work by Otsuji's group to apply this plasma wave concept into smart photonic network system [5]. We have also reported a theoretical transverse magnetic (TM) mode analysis of the behavior of surface waves in bulk and 2DEG semiconductor plasma under drifting conditions [6,7]. Our theoretical results on the interactions of plasma waves with the EM waves produced by interdigital slow-wave circuits indicated the occurrence of negative conductance in two-terminal interdigital admittance, when the carrier drift velocity slightly exceeds the phase velocity of the fundamental component of the EM waves.

The purpose of this paper is to investigate the existence of surface plasma wave interactions in 2DEG at a modulation-doped heterointerface. The AlGaAs/ GaAs interdigital-gated high-electron-mobility transistor (HEMT) devices were fabricated and their input admittances were measured in microwave region and compared with theoretical predictions. The possible application of a plasma wave HEMT device was also considered.

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2. Device Structure and Measurement

Among novel modern structures, AlGaAs/GaAs heterostructures have emerged as the most popular material for confining electrons. The sample is a AlGaAs/GaAs modulation-doped heterostructure grown by molecular beam epitaxy. The interface of n-doped AlGaAs layer and undoped GaAs layer defines a two-dimensional electron gas (2DEG) system where electron motion perpendicular to the layer is frozen out, thus producing highly mobile electrons. The thickness of the main layers, from bottom to top are as follows: 500nm GaAs buffer layer; 100nm AlGaAs buffer layer; 20nm undoped GaAs layer; 10nm AlGaAs spacer layer; 50nm n-doped AlGaAs (Si δ doping) barrier layer; 10nm GaAs undoped cap layer. The devices were designed and fabricated using electron beam lithography and a standard lift-off technique. The channel width, W, was 50 mm. The carrier mobility and the carrier sheet density obtained by Hall measurements at room temperature were 7540 cm^2/Vs and 4.6 x 10^{11} cm^{-2}, respectively.

A device with dc connected interdigital finger structure as schematically shown in Figure 1 was used in this study. As shown at the top of Figure 1, the interdigital slow-wave circuits consist of two comb-like electrodes and have 25 pairs of fingers/channel with a finger pitch, p, of 5 and 10 μm. The finger width and spacing are chosen to be the same and equal to a, so that p is equal to $2a$. In the present device design, two channels were formed.

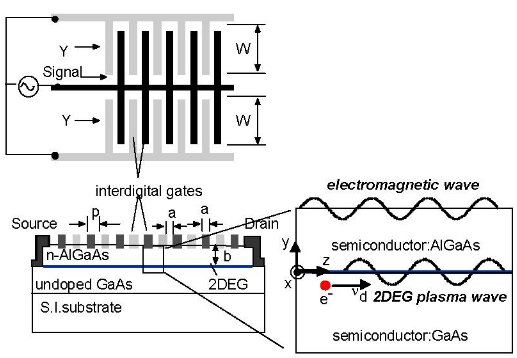

Figure 1: Physical device structure of AlGaAs/GaAs interdigital-gated HEMT device.

This device is similar to conventional HEMT in which a set of interdigital electrodes act as a Schottky gate. However, the use of the device is very different. We are interested in the two-terminal admittance of the interdigital gate itself, which should be strongly modulated and even becomes negative in its real part due to the wave interactions between plasma waves and EM waves as shown schematically at the bottom of Figure 1. The device has the overall structure of a loaded coplanar waveguide (CPW), which facilitates on-chip microwave probing. A plan view of the fabricated device is shown in Figure 2. The two-terminal admittance, Y, of the plasma wave device was determined from the S-parameter reflection measurement, as shown in Figure 2 over the frequency range from 1 to 20 GHz at room temperature. Here, only one port was probed while another port was kept open. During the measurement, the source and drain were biased with dc voltage, V_S and V_D, respectively to cause drift current to flow in the channel while the dc voltage to the set of interdigital fingers was kept at zero. The reflection S-parameter measurement was carried using a vector network analyzer HP8510C and a Ground-Signal-Ground (G-S-G) type Cascade on-wafer microwave microprober. Such microprobers enable low parasitic connections to be made to the devices.

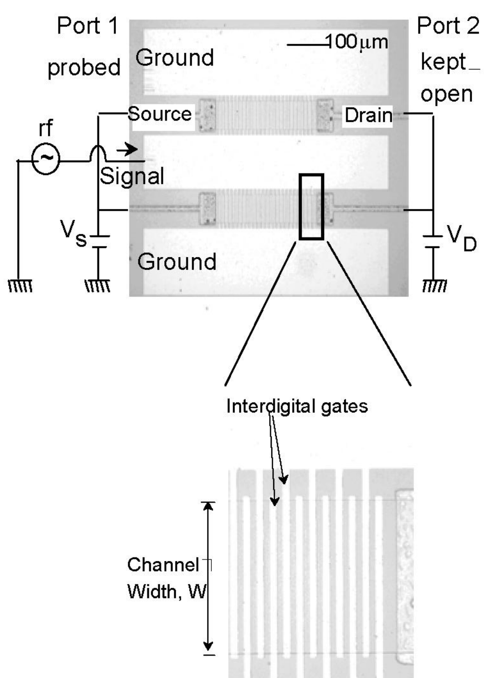

Figure 2: Plan-view of fabricated AlGaAs/GaAs interdigital-gated HEMT device.

First, the input reflection coefficient, Γ, in complex form were measured. Then, these measured coefficients were used to find the impedance, Z. Finally, the obtained impedances multiplied by 50Ω were used to derive the admittances by simple conversion process. It was shown theoretically in reference [6,7] that traveling-wave interaction becomes more and more favorable at higher frequencies, particularly in the THz region. However, direct measurement of two-terminal admittance at such ultra-high frequencies is very difficult. Therefore, the measurements are carried out only at low microwave frequencies.

3. Experimental Results

The dc current controllability of the interdigital gates in the HEMT structure was investigated. Figure 3 shows typical dc current-voltage (I-V) characteristics when the gate voltage was applied to all interdigital fingers. The device fabricated shows well-behaved dc I-V characteristics similar to a normal Schottky-gate field-effect transistor (FET). This indicated that a set of interdigital finger gates can behave as a conventional Schottky gate with good controllability of 2DEG under the interdigital gates.

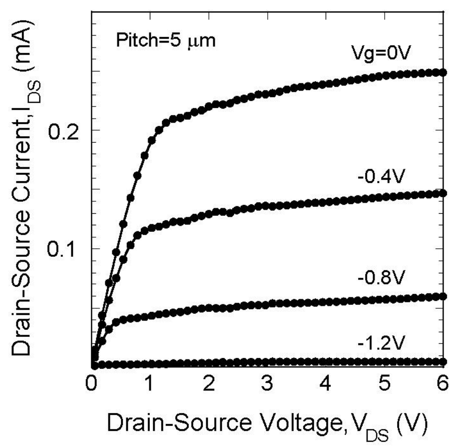

Figure 3: DC I-V characteristics of fabricated AlGaAs/GaAs interdigital-gated HEMT device.

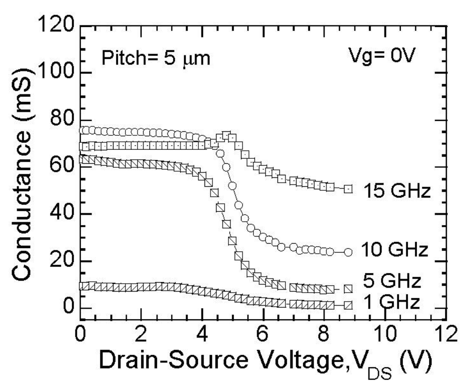

Figure 4: Measured conductance characteristics as a function drain-source voltage.

The measured values of the microwave conductance of the two-terminal interdigital structure is shown in Figure 4 as a function of the drain-source voltage, V_{DS}, for a device with a pitch of 5 μm under zero gate voltage for all the interdigital fingers. Figure 4 show that measured values of conductance experience remarkably large changes with changes of the drain-source voltage for all the measured frequencies.

In particular, the conductance decreases rapidly at 5 and 10 GHz when the drain-source voltage slightly exceeds 4V. Obviously, the observed behavior of the conductance of the interdigital gates cannot be explained at all by the conventional transport theory with the transit time picture. These results indicate the presence of the effect of the interactions between the surface plasma waves of 2DEG carriers and EM waves in the fabricated interdigital-gated HEMT device.

4. Theoretical Results

A theoretical analysis based on the transverse mode (TM) analysis presented in reference [6,7] was applied to confirm the presence of such an effect quantitatively. The calculation results of the interdigital conductance based on our theoretical approach is shown in Figure 5. Figure 5 shows that calculated values of conductance also experience remarkably large changes with changes of the drain-source voltage for all the calculated frequencies. Here, small value of negative conductance was obtained.

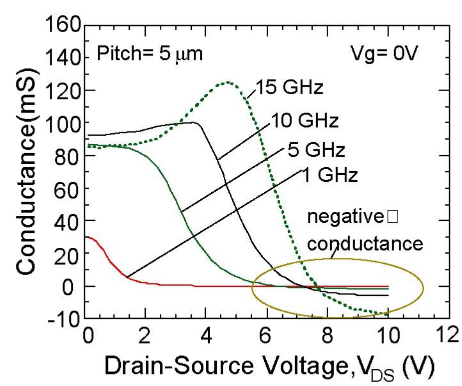

Figure 5: Calculated conductance characteristics as a function drain-source voltage.

As seen in the Figure 5, the calculated values of conductance have nearly the same magnitudes as the experimental ones. Thus, the general behavior of the conductance is reproduced surprisingly well by calculation in spite of various assumptions used in the theory. The major assumptions in the theory are: (1) the interdigital pattern is infinitely repeated; (2) the thickness of the electrode pattern is infinitely thin, but its conductance is infinitely large; (3) the phase of the EM field on the metal is maintained the same in the finger direction for all frequency components; and (4) the carriers have the same drift velocity along the whole channel.

In spite of the above general remarks, however, agreements on the details are obviously not adequate between theory and experiment. Particularly, the appearance of small negative conductance is predicted by theory at drain-source voltages above 7.5V for frequencies ranging from 10 to 15 GHz, and this behavior was, unfortunately, not seen in the experiment.

We believe that the major cause for the lack of agreement in the detailed behavior comes from the assumption (4) in which the carriers have the same drift velocity along the whole channel. This is not the case in any semiconductor field-effect transistor under a strong drain bias. The nonoccurrence of negative conductance in the experiment can be explained in terms of cancellation of the small negative conductance obtained under the high field portion of the channel by the large positive conductance coming from the low field portion of the channel.

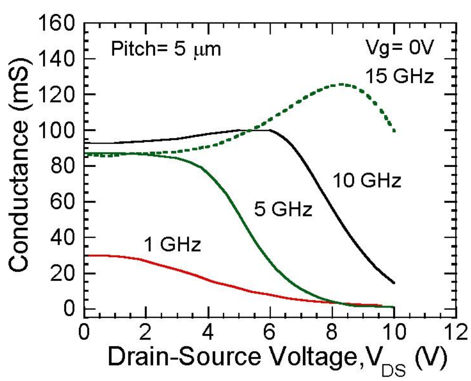

Figure 6: Re-calculated conductance characteristics as a function drain-source voltage taking into account the nonuniformity of field distribution along the HEMT channel.

To take account of this effect, we have estimated the electric field distribution, $E(z)$ under the interdigital gates by fitting the dc drain I-V characteristics using the gradual channel approximation and the field-dependent mobility. The derivation of $E(z)$ is presented in reference [8]. Here, we replace the entire interdigital pattern with one gate electrode, since the surface potential of the air-gap region is similar to that underneath gate with zero-bias due to strong Fermi level pinning. From the estimated field distribution, we obtained the drift velocity under each interdigital finger, υ_d^{finger}, using the following equation,

$$\upsilon_d^{finger} = \frac{\mu_0 E(z)^{finger}}{1 + \frac{\mu_0}{\upsilon_s} E(z)^{finger}} \qquad (1)$$

where μ_0 is the low-field mobility and υ_s is the saturation velocity. Then, the interdigital conductance is obtained from the following equation,

$$Y = \sum_{finger} \left(G^{finger} + jB^{finger} \right) \qquad (2)$$

where G^{finger} and B^{finger} are the conductance and susceptance of the individual interdigital fingers, respectively. For the values of G^{finger} and B^{finger}, we used the values assuming uniform velocity distribution, taking advantage of gradual changes in velocity along the channel and the quasi-periodic nature of the interdigital pattern.

The calculated conductance taking into account the nonuniformity of the field in this fashion is shown in Figure 6. The calculated results show much better agreements with the experimental ones shown in Figure 4 in spite of a very simple theoretical treatment of a very complicated problem. Thus, it can be concluded that the observed changes in conductance is due to the coupling between the drift plasma waves in the 2DEG carriers and the EM waves through the interdigital pattern.

5. Discussion

Although net negative conductance was not observed in the current fabricated device, a very large conductance modulation was realized in the microwave range even in a comparatively large device of micrometer-scale size. For example, the conductance change, ΔG, experimentally observed between V_{DS} = 4 and 8 V is plotted in Figure 7 as a function of the measured frequency. It clearly shows that the conductance change is more than 1000 mS/mm in spite of the fact that the electrode width and pitch were much larger than those of conventional transit-time devices. The conductance change shows a peak at a certain frequency whose position can be controlled by changing the pitch of the interdigital gates.

It is expected that the characteristics obtained for the interdigital device fabricated may have the potential to be applied for a microwave impedance modulating or switching operation. This device may be used, for example, for a proximity communication system where it can be coupled with an on-chip dipole antenna several millimeters in size.

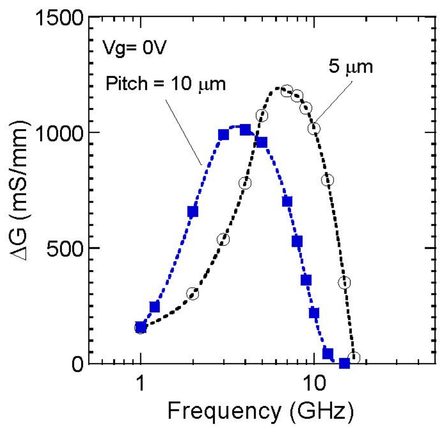

Figure 7: The conductance change, ΔG between V_{DS} = 4 and 8 V as a measured frequency.

The structure of on-chip dipole antenna and its return loss characteristics is shown in Figure 8. The simulation was performed using commercialized Sonnet Lite 9 high frequency electromagnetic software.

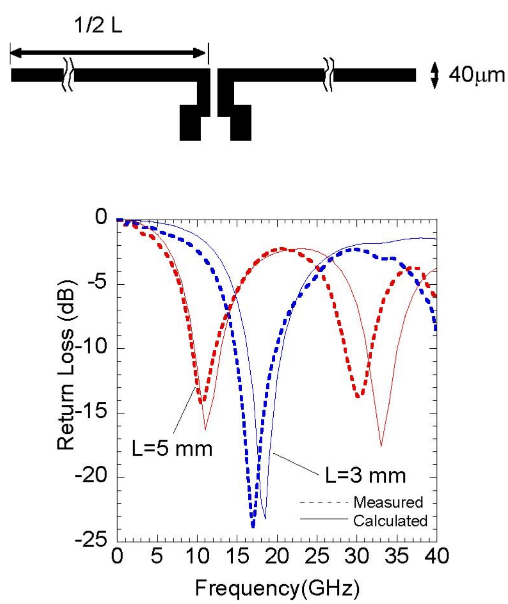

Figure 8: On-chip dipole antenna structure and its return loss characteristics.

It can be seen in Figure 8 that an antenna with L=5 mm showed high return loss characteristics up to -15dB at 10 GHz. As shown in Figure 7, the interdigital-gated plasma HEMT device with a pitch of 5 μm also showed a peak at around 10 GHz. Thus, it can be simply said that plasma HEMT device can be directly integrated with on-chip dipole antenna without any matching circuits for use in a proximity communication system.

6. Summary

The existence of traveling wave interactions was successfully demonstrated using the proposed interdigital-gated HEMT device. The obtained characteristics can be used for high frequency applications such as high-speed switching devices in a proximity communication system. The net negative conductance should be obtainable even at lower microwave frequencies if a uniform field distribution under the interdigital gates can be realized. The development of planar type THz antenna is highly demanded ir order to perform measurement in the THz region where the interactions of plasma wave is more favorable in this region.

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