Microelectronics Journal 38 (2007) 1263–1267

Microelectronics Journal

www.elsevier.com/locate/mejo

# Integration of interdigital-gated plasma wave device for proximity communication system application

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Received 23 July 2007; accepted 30 September 2007
Available online 13 November 2007

**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 5 and 10 GHz 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; GaAs

## 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 strong 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 500 GHz, 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 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)

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0026-2692/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.mejo.2007.09.028

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.

## 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: 500 nm GaAs buffer layer; 100 nm AlGaAs buffer layer; 20 nm undoped GaAs layer; 10 nm AlGaAs spacer layer; 50 nm *n*-doped AlGaAs (Si $\delta$ doping) barrier layer; 10 nm 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 $cm^2/V\,s$ and $4.6\times10^{11}\ cm^{-2}$, respectively.

A device with dc connected interdigital finger structure as schematically shown in Fig. 1 was used in this study. As shown at the top of Fig. 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.

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 Fig. 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 Fig. 2.

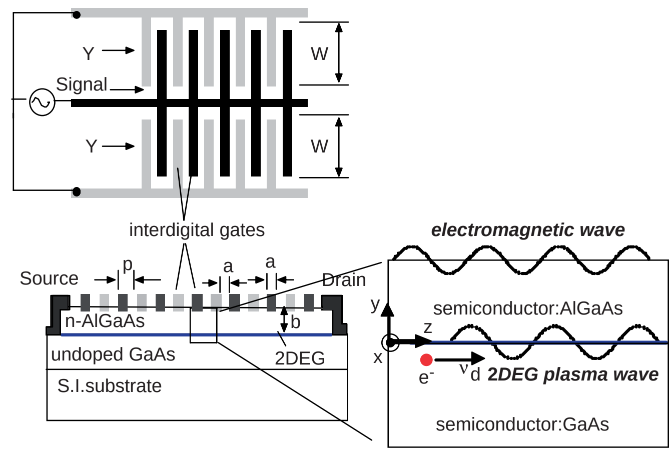


Fig. 1. Physical device structure of AlGaAs/GaAs interdigital-gated HEMT device.

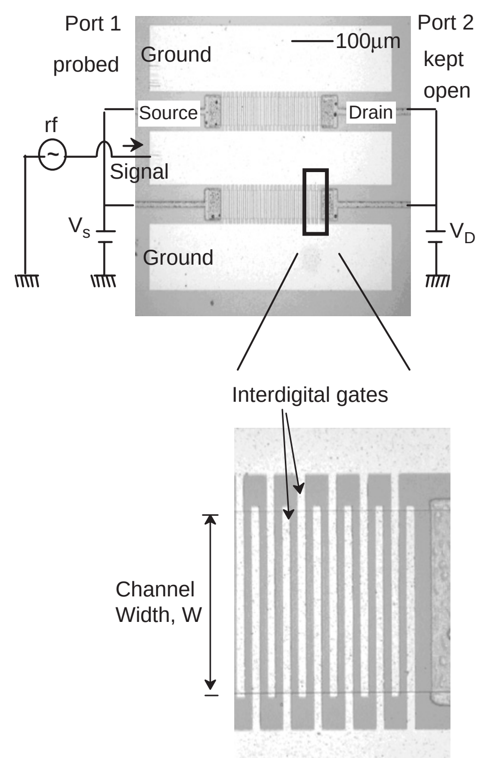


Fig. 2. Plan-view of fabricated AlGaAs/GaAs interdigital-gated HEMT device.

The two-terminal admittance, $Y$, of the plasma wave device was determined from the S-parameter reflection measurement, as shown in Fig. 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