Characterization of Ultrafast Devices Using Near-Field Optical Heterodyning

M. E. Ali, K. Geary, H. R. Fetterman, S. K. Han, and K. Y. Kang

Abstract—**We demonstrate a novel technique for highly localized injection of millimeter waves in ultrafast devices that combines optical heterodyning and near-field optics. The technique relies on evanescent coupling of two interfering lasers to a submicron area of a device by means of a near-field fiber optic probe. Scanning measurements show the dc and ac photoresponses of two ultrafast device structures, namely low-temperature GaAs photoconductive switches and InP-based high electron mobility transistors. The response characteristics were rich in structures that revealed important details of device dynamics.**

Index Terms—**High electron mobility transistors, millimeter-wave generation, near-field optics, optical fiber probes, optical heterodyning, photoconductive switches, photodetectors, phototransistors, ultrafast photoresponse.**

I. Introduction

NEAR-FIELD optical heterodyning (NFOH) is a novel technique for the injection of millimeter waves at any arbitrary point of an ultrafast device or circuit with high degree of spatial localization [1]. It has the capacity to provide details of the operation of a probed device which are inaccessible using conventional means. The method involves optical mixing of two lasers in a tiny area of the device using near-field coupling. The lasers are set apart in frequency by a desired amount which is tunable over hundreds of gigahertz. A near-field fiber-optic probe, which has a sub-wavelength aperture, couples the lasers evanescently to the device from a distance of ∼100 nm. The illumination spot, which is aperture-limited rather than diffraction-limited, has approximately the same size as the aperture and defines the point of optical interaction. The local density of photogenerated carriers at this point oscillates at the difference frequency and produces millimeter waves. The response of the device to such a localized source of millimeter waves is then observed at its terminals. In previous work, the validity of the NFOH technique has been verified up to 100 GHz for heterojunction phototransistors [1]. There, measurements were restricted only to a specific point of the device. In this paper, we present the results of more comprehensive measurements, in which we performed a scan across the entire device under test. These results show both the resolution capabilities of NFOH and the type of details one can obtain regarding the dynamics of ultrafast devices. Photoconductive switches and high electron mobility transistors (HEMTs) were tested to illustrate the versatility of the technique.

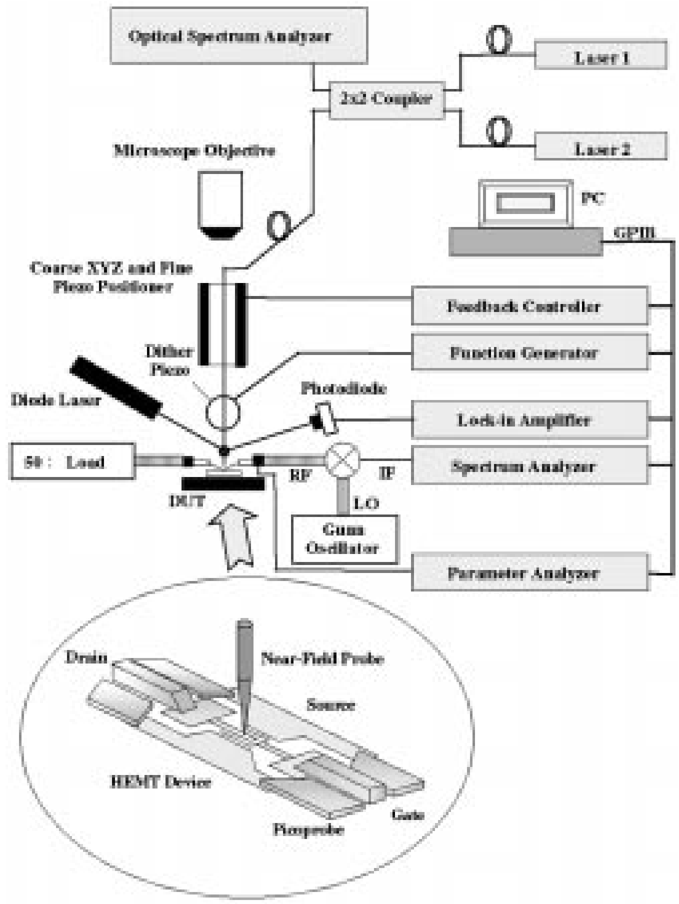

Fig. 1. Experimental setup for the near-field optical heterodyne measurements.

II. Experimental Setup

Our experimental arrangement, as shown in Fig. 1, consisted of a laser mixing setup, a near-field scanning system, and a high-frequency probing and measurement setup. The laser mixing setup employed a tunable dye laser and a temperature stable HeNe laser with a difference frequency tuning range of several hundred GHz around the HeNe wavelength of 632.790 nm. The laser beams were combined using a fiber-optic coupler, one output of which was coupled to a bare-ended fiber with the bare

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Fig. 2. Device geometry of the photoconductive switch. The near-field scan was performed from X to X'.

end fusion-spliced to a near-field fiber-optic probe. The probe was fabricated using a laser-based micropipette puller and had a tip of ~1-mm taper length and ~100 nm aperture size. The near-field scanning system, actively stabilized by a shear-force feedback mechanism [2], ensured stable positioning and scanning of the fiber probe with high precision. Thus, the system allowed us to scan the probe across the device at a constant separation of less than ~100-nm. The high frequency response of the device was observed at its terminal using coplanar RF probes and a millimeter-wave receiver which consisted of a mixer, a Gunn diode as the local oscillator, and intermediate frequency amplifiers.

III. Study of Photoconductive Switches

Low-temperature grown GaAs (LT-GaAs) has attracted a lot of interest recently for its use in photoconductors because of its outstanding electrical properties, such as short carrier lifetime, high dark resistance, and high breakdown field. These devices exhibit sub-picosecond impulse photoresponse and can be very useful in high-speed photoconductive sampling applications. Characterization of photoconductive switches using our NFOH technique will provide a better understanding of these devices at high frequencies.

The geometry of the LT-GaAs photoconductive switch used in our experiments is shown in Fig. 2. The details of device growth fabrication can be found in [3]. The device consisted of two coplanar metal strips of width 75 μm, separated by a gap of 15 μm. One of the strips had a 15-μm gap, intended for sampling electrical transients propagating along the lines. This gap was investigated in our near-field heterodyne measurements. One-dimensional scans were performed across the gap from X to X' as shown in Fig. 2 at a tip-sample separation of ~100 nm. The X-end of the gap was biased at 30 V with respect to the X'-end.

Results of our near-field scanned measurements of the photoconductive gap with optically injected signal at 63 GHz are shown in Fig. 3. The topological profile of the gap was obtained from the feedback signal in the scanning system and is presented in the figure so that the response of the device can be correlated to its structure. The signal strength, measured in a heterodyne millimeter wave receiver, is plotted as a function of the scanning coordinate. The response was strongly peaked at the edge of the positive electrode, and negligible over the rest of the gap, except for another small peak at the edge of the negative electrode. Alexandrou *et al.* observed similar variation of the signal strength as a function of the excitation position for semi-insulating GaAs photoconductive switches under pulsed optical excitation [4]. Their photoconductive gap was 50-μm wide and the excitation beam size was 3 μm in diameter. The NFOH technique allowed for the study of a much shorter gap, and for our case, with higher resolution. Moreover, because

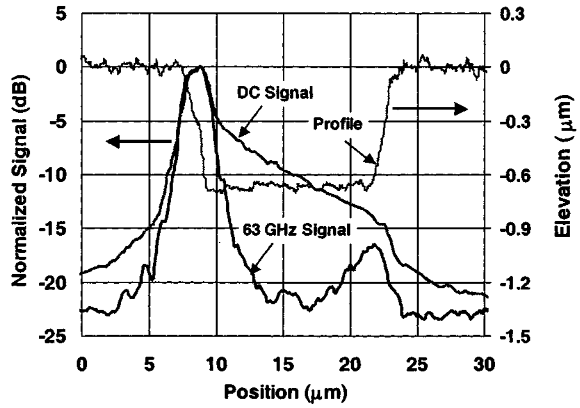

Fig. 3. DC and ac response of the photoconductive switch in the scanned direction. The profile of the device is also shown.

of optical heterodyning, the excitation was a narrowband millimeter wave signal that permitted us to probe the device at a specific frequency.

The peak response at the edges can possibly be understood from the theory developed by Sano and Shibata [5]. According to their theory, the illuminated part near the edge has a higher conductance due to the photogenerated carriers, that causes a decrease in the local field leading to field redistribution in the gap. Through this mechanism, a time varying incident light produces a displacement current at the electrodes, whose strength depends on the magnitude of the local field at the point of illumination. The strong response peak in Fig. 3 is, thus, an indication of the presence of a strong electric field at the anode edge. Similar field enhancement near the anode was experimentally observed and studied for metal/semi-insulating GaAs structures [6].

Fig. 3 also indicates a peak in the dc response near the anode. However, the dc response is substantial over the entire span of the gap, unlike the ac response. We believe the dc response is due to the drift of the long-lived photogenerated carriers. Because of the long lifetime, these carriers do not contribute to the ac response. A possible explanation for the observed variation of the response over the gap can be attributed to its nonuniform field distribution. The high-frequency near-field response of the device can be related to the local electric field and the effective lifetime, τ, of the photogenerated carriers. It is, then, possible to extract the total electric field distribution by correlating the measured data with a physical model that characterizes τ specific to the probed device. Alternatively, one can determine τ experimentally from time-resolved near-field measurements.

IV. Study of HEMTs

HEMTs are very promising devices for photonic millimeter wave applications because of their excellent low noise and ultrafast electrical and optical performance [7]. For the measurement of the optical response of HEMTs, both frequency-domain techniques, such as optical heterodyning and time-domain techniques, such as picosecond electrooptic sampling, are frequently used [7]. These techniques use conventional optics which can only produce a diffraction limited spot size of ~10 μm. For ultra-small devices, they can only measure the response of the

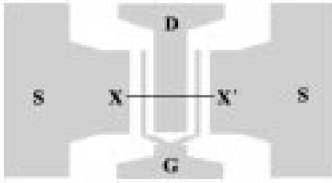

Fig. 4. Layout of the HEMT device. The near-field scan was performed from X to X'.

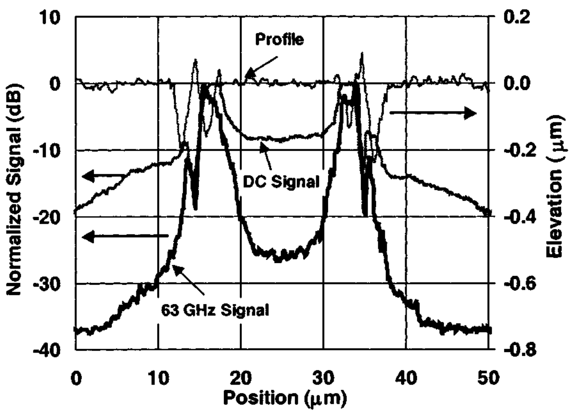

Fig. 5. DC and ac response of the HEMT device as a function of the point of injection of the millimeter-wave signal. The profile of the device is also shown.

device as a whole. This limitation is overcome in our present set of measurements using the NFOH technique.

For our measurements, 1-μm-gate pseudomorphic InAlAs/InGaAs/InP HEMTs were used [7]. The layout of the device is shown in Fig. 4. The device had a double-fingered gate structure with a length of 1 μm and a width of 80 μm for each finger. The central drain strip was 15-μm wide. The gate-to-drain and the gate-to-source spacings were 2 μm each. The NFOH scan was performed along the line X–X' as indicated in Fig. 4.

Fig. 5 shows the response of the device as a function of the point of illumination. The device was biased at a drain to source voltage of 1.5 V and a gate to source voltage of -0.2 V. The ac response exhibited multiple peaks. Identification of the peaks with the different parts of the device can be done using the topological profile, which is overlaid with the response characteristics in Fig. 5. The strongest peak occurred at the edge of the gate on the drain side. The other dominant peak occurred at the gate edge on the source side. The depression in the signal strength between these two peaks can be associated with the gate metallization, as the device was illuminated from above. The difference in signal strength between the two edges of the gate was $\sim$10 dB, although the edges were only 1 μm apart. This significant difference resulted from the vastly different field strength between the drain and source sides of the gate. For the bias used in our measurements, the HEMT device operated in the saturation regime. In this regime, a high-field region exists on the drain side of the gate. The efficient and fast collection of the photogenerated carriers in the high field leads to a stronger response, as observed in our measurements. Thus the NFOH scan is capable of identifying regions of enhanced activity of the carriers with high spatial resolution, which is very important for a better understanding of the operation of the device.

The dc photocurrent also indicates regions of enhanced response, as shown in Fig. 5. Particularly, the device exhibited significant dc response with illumination in the gap between the drain and the gate. However, compared to the 63-GHz RF response, the dc response is characterized by the absence of sharp peaks at the edges of the gate. The response of the HEMT device at high frequencies was determined primarily by the transit time of the photogenerated carriers under the gate. As the illumination point was moved away from the gate edge, the transit time increased leading to a deterioration of the ac response. In contrast, the dc response was dominated by the presence of long-lived carriers and by a number of slow gain mechanisms [8]. Although these slow processes were enhanced in high-field regions, such as in the gate-to-drain gap, they may not particularly depend on the distance of the excitation point from the gate edge. The slow processes also account for the higher dc residual signals due to scattering when scanning over metallized regions.

V. CONCLUSION

We have demonstrated the applicability of the NFOH technique for the characterization of ultrafast devices by performing successful measurements on photoconductive switches and HEMTs. The technique provides a novel way of examining devices in both the frequency and spatial domain with high resolution. It can identify unprecedented details of dynamic microscopic phenomena, thus establishing itself as a powerful tool in the exploration, diagnostics, and design of ultrafast devices and circuits.

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