THz Imaging for Failure Analysis of RF Circuit

Md Rezaul Hasan, a,4 Md Shamiul Fahad, b and Mulpuri V. Rao a

a Department of Electrical and Computer Engineering, George Mason University, Fairfax, Virginia 22030, USA
b Division of Electrical and Computer Engineering, Louisiana State University, Baton Rouge, Louisiana 70803, USA

THz imaging and sensing have been demonstrated to be useful for various applications such as security inspection, 1 spectroscopic characterization of materials 2 and biomedical applications of cancer research and DNA analysis. 3–5 Many of these applications exploited the unique properties of terahertz radiation which include the transparency of common packaging materials, and unique spectral fingerprints of many chemicals in terahertz range. 5 Understanding the mechanism of coupling of radiation is another important application of THz imaging. 6–8

The resolution of the THz imaging in the free space is limited by the diffraction limit and could not be any smaller than a half of the wavelength. However, designing a specific metal layout at the surface may allow excitation of the evanescent THz waves, providing the subwavelength resolution imaging capability. Using a field effect transistor for sub-THz imaging was demonstrated in literature. 9,10 In this work, for the first time, the potential application of THz imaging for failure analysis of an RF circuit has been demonstrated. The shift of the THz images obtained for different configurations was explained by the effects of contact pad geometry and bonding wire orientation on coupling of sub-THz radiation and the sensitivity of photoresponse on drain voltage in each channel of the device. It was shown that small variation in the distribution of the total drain current between the channels would cause noticeable distortion of the sub-THz reponsivity image of the device under study. Scanning images of different devices in the RF circuit and comparing them with the images of the etalon device, it will be possible to identify the defective devices, as well as the possible locations of defects. This will create an opportunity for the noninvasive and nondestructive failure analysis of power RF circuits under sub-THz radiation. With further increase in the frequency and the spatial resolution, the analysis of smaller devices will also become possible.

Experimental

300 GHz CW radiation beam, modulated by a mechanical chopper with a modulation frequency of 200 Hz was focused on the device using a parabolic mirror. The radiation-induced voltage change at the drain of the device, caused by excitation and rectification of plasmonic oscillations in the device channel, 11,15 was recovered by a lock-in amplifier. The optics and the lock in technique used in this experiment, is similar to standard photodetection methods described in literature. 11–15

The device was mounted on a 3D nanopositioning stage, which was movable in x, y, and z directions by a computer program with a 1 μm resolution to record spatial variation images. External batteries were used to bias the drain and gate of FET under study. The spatial variation dependent photoresponse images were taken by raster scanning from −2 mm to +2 mm in both x and y directions with a step of 0.07 mm and with 2 s delay time between consecutive steps. The applied biases were V GS = −2.75 V and V DS = 200 mV in all the experiments.

Results and Discussion

Figure 1a shows the optical image of a commercial RF FET having 3 shorted drain pads and 2 shorted gate pads. The device has interdigitated source and drain pads with 20 parallel channels and small gate fingers of 1 μm. The geometrical angle between pin-1 and pin-2 is 40°. Device width is 500 μm. One bonding wire is attached to each drain and gate pad and 3 bonding wires are connected to a large source pad. The effects of the THz radiation coupling and the current distribution inside the device channels on the device photoresponse were observed by separately energizing different bonding wires and moving the focus of the THz beam along the device surface. Figure 1b shows the terahertz photoresponse vs gate voltage curves for different applied drain voltages. The gate bias dependent photoresponse curve shows that photoresponse reaches to maximum value near V D. The peak position shifts toward more negative gate voltages with the increase of the drain bias, which is consistent with reported data. 11,15 At zero drain bias, the induced photocurrent was 2.8 μA. When the drain bias is applied, the asymmetry between the source and drain is further increased which assists more coupling of radiation. As a result, induced photoresponse increased with higher drain bias and the maximum of 84 μA was induced at V DS = 890 mV. All the sub-THz images were captured with an applied bias of V DS = 200 mV and V GS = −2.75 V. Figure 1c shows the Noise Equivalent power (NEP) [left black scale] and Responsivity [right red scale] graphs against the gate voltage. A maximum responsivity of 2.5 mW/√Hz is obtained near V D = −2.75 V. NEP reaches the minima at −2.5 V and tends to rise after that and at −2.75 V, the value of NEP is 5 × 10−6 W/√Hz. The minimum value of NEP for this device is 7 × 10−7 W/√Hz.

Figure 2 shows the spatial variation of induced photoresponse for different connection configurations. Figure 2b shows that the image is not sensitive to the position of source bonding wire. Only the source bonding wire position is changed from S3 to S1, keeping drain and gate pad and bonding wire unchanged and it showed no change (neither shift of image nor the direction) in the image. To understand the effect of gate coupling on the spatial variation of photoresponse, Figure 2c is plotted by showing two images, generated by altering only the gate pad’s position and it showed no change in the image as well. But, the last set of images (Figure 2d) confirmed the effect of drain coupling on the THz imaging. Once the drain pad D3 is energized instead of
Figure 1. (a) Image of the GaN/AlGaN FET, (b) Terahertz photoresponse vs V_{GS} for different V_{DS} (Inset shows I_{DS} vs V_{GS} characteristic curve), (c) Responsivity (right axis) and NEP (left axis) vs Gate voltages.

Figure 2. (a) Multi channel MOSFET Device with pad notation (which are used to refer to the pin combination for each image), (b) Change of source bonding wire position does not impact the image, i.e., no change of direction of image [changed pad is marked in red to highlight], (c) Change of gate bonding wire position has no effect on the image and (d) Change of drain pad changes the direction of image. This is correlated to the geometry of the bonding wire orientation.
Figure 3. (a) Equivalent RF circuit for coupling of 300 GHz radiation with Pin 2 connected, (b) Equivalent DC circuit with induced DC voltage and (c) Change of THz imaging pattern. Left image is generated when pin 1 is activated, while right image is generated when pin 2 is activated.

D1, then the image is tilted to 40° without changing the focus center. Now interestingly, the geometrical angle between these two bonding wires is 40° (Figure 2a). So, the orientation and geometry of drain bonding wire is basically defining the angle of image. In summary, the shift of the center and angle of the image is caused basically due to geometry and coupling of radiation by drain pad, but it is almost insensitive to source and gate pad’s geometry or respective bonding wire position.

Figure 3a shows the equivalent RF circuit which couples the 300 GHz radiation through the gate of transistor and due to asymmetry between source and drain, it induces a constant DC voltage between these two nodes. Pin 1 and pin 2 represent the bonding pad connected to two different drain pads, but they are shorted through a metal. Resistance of that shorting metal is 4 Ω. Photoresponse voltage is induced in all the channels of FET. To understand the effect of geometry of drain pad and bonding wire, only two groups of channels are shown in the equivalent circuit. The effect of location of energizing pad on the photoresponse is significant. The photoresponse images clearly show different shapes due to the location of drain pad being energized. Figure 3b shows the equivalent DC circuit after the constant DC voltage is induced between source and drain. When pin 2 is connected, the channels closer to that pin, have more incoming current. Coupling of THz radiation depends on the relative beam position with respect to the bonding wires. The photoresponse induced by different channels decreases with distance from the activated pin. Due to the resistance of the connecting metal between pin-1 and pin-2 (though as small as 4 Ω from Figure 4a inset), voltage is dropped in the connecting wire. And as the photoresponse is very sensitive to small change of drain voltage, so it varies significantly between the channels adjacent to pin-2 and channels adjacent to pin-1. Figure 3c shows the THz images, obtained by scanning the surface of the transistor with the THz beam. Maximum response position is shown with a white dot in both images. When pin 2 was activated, the image was tilted with an angle of 40° (right image) with respect to the image, obtained with energization of pin 1 (left image). The maximum response point of the image was also shifted upward by 500 μm. This phenomenon can be explained from the geometry of this two pads. The distance between the two pads is 500 μm, which contributes in shifting of the position of the photoresponse maximum. Image tilting is also evident, which is due to the geometrical orientation of the two drain pads (Fig. 1a).

A quantitative analysis was done to understand the effect of slight variation of drain voltage on photoresponse. Figure 4a shows the Id-Vd characteristic curve of the device and the current in the channel is 15 mA at Vd = 200 mV (drain bias used for imaging) and Vgs = −2.75 V. The inset shows the I-V curve between pin-1 and pin-2. Bus resistance between the two pins is extracted as 4 Ω from this graph. That gives the voltage drop between pin-1 and pin-2 as 60 mV (4 × 15). That means, if 200 mV is applied at pin-2, then the intrinsic drain voltage near pin-1 is only 140 mV. Figure 4b shows the photoresponse vs drain voltage characteristic curve. Sharp rise of the photoresponse with a slight change in drain voltage is very evident from the graph. Due to 60 mV difference in drain voltage, the

Figure 4. (a) Ids vs Vds characteristic curve of FET (Inset shows the I-V curve between pin 1 and pin 2, (b) Photoresponse vs Drain voltage curves measured at pin 1 and pin 2 overlap. Arrows show photoresponse values measured at pin 1 and pin 2 when pin 2 is energized, accordingly.

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photoresponse of the group of channels located near pin-1 is reduced to almost half of the photoresponse of group of channels located near pin-2. So, the potential difference between the two drain pads also affected THz imaging. This voltage difference causes different portions of the multi-channel FET to excite differently than the other portions for different connection configurations and thus the image pattern changes.

In summary, room temperature sub-THz imaging showed the effect of contact pad geometry, bonding wire orientation and drain voltage variation in different portion of a device on coupling of radiation. Images were dependent on selective activation area. This paves the way for potential application of THz imaging for failure analysis of RF circuit.

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