

Active Laser Characterization by Scanning Capacitance Microscopy

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ABSTRACT

This research work is to develop a high precision structural analysis and failure analysis technique based on scanning probe microscopy, which is suitable for practical compound semiconductor manufacturing support.

INTRODUCTION

In view of the aggressive down scaling and the increasing complexity of devices (for instance, InP-based laser for fiber telecommunications), new characterization tools are required, which satisfy several requirements such as more than two-dimensional profiling capability, nm scale resolution, time efficiency for practical industrial use^{1, 2}. SCM emerges as one of the best candidates so far^{3, 4, 5}. Basically, using an Atomic Force Microscope a conductive probe is scanned over the cross section of the device and forms a micro MIS capacitor whereby a high frequency capacitance signal is extracted by a specific RF circuit. Since the capacitance of the MIS structure is strongly linked with the free carriers underneath the probe, SCM is used as 2D free carrier characterization tool on passive VLSI devices in both research and manufacturing phase. The major advantage of this technique is that it combines high spatial resolution (down to 20nm) and high sensitivity in carrier concentration profiling in an intrinsic 2D mapping, which is suited for complicated structures. However, the main limitation is that the sample preparation process is not yet satisfying, quantitative data interpretation and precise junction delineation are difficult to obtain.

Within this paper, we extend SCM from silicon-based VLSI devices to compound semiconductor devices, from passive devices to active devices. We present a completed procedure of this new extension mode of SCM, including sample preparation and packaging, measurement setup and results interpretation. It provides a direct method to understand the physics of real devices under operating conditions, which can also be linked to theoretical predictions using device simulations. Moreover, it also allows failure analysis for the device processing support in industry manufacturing.

EXPERIMENTS

The SCM measurement setup (based on an AFM Dimension Model 3000 from digital instrument) with the capacitance sensor is shown in figure1 (a), whereby a RF (at around 915MHz) resonant circuit is used to extract the local capacitance signal while the conductive probe is moving over the region of interest. Only the majority carriers in the region underneath the scanning probe can follow the AC driving voltage. Note that this operating mechanism of SCM is very important in understanding the extension of SCM to an active device as done in our experiments. The measured samples are mounted on a standard package box, with its cleaved cross-section exposed to the scanning probe. By wire bonding (see figure1 (b)), two terminals of the measured device are connected with pins, which enables applying a bias during the measurement.

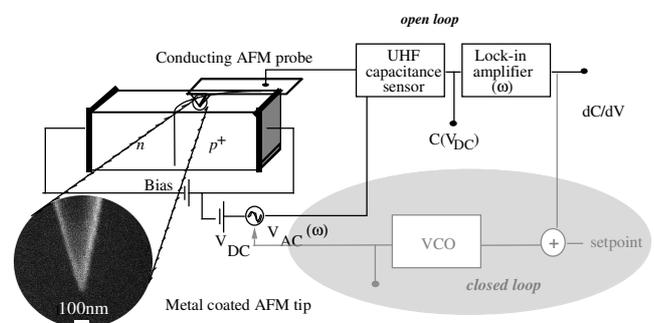


Figure1 (a): SCM setup for active device measurements

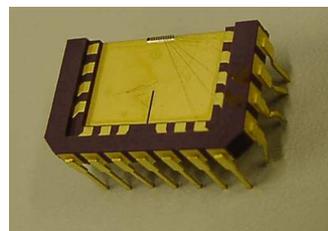


Figure1 (b): sample packaging by wire bonding

RESULTS AND DISCUSSION

The carrier profile of this device is shown in figure2, as measured by SSRM⁶. Above the n-type doped substrate (on the left side of the image), a mesa is heavily Zn doped as the current channel. Two multilayered (p-n-insulating-n-p) arms are close to the mesa. Note that sandwiched semi-insulating layer in the middle is Fe doped, which is used for both current confinement and optical confinement. The two n-type layers in-between are used as barrier to prevent the inter-diffusion between the Fe and Zn. As we know, the lateral current confinement is important in such kind of laser structure, which can substantially improve the performance. The critical region requiring attention here is the bridge region (marked with a circle), which connects p-type mesa and p-type layer in the arms. Here the n-p-n structure forms a reversed junction and the bridge forms a very thin channel. Due to its functionality in confining the lateral current, it is carefully designed and fabricated to reduce the extra current as much as possible when the diode is forward biased.

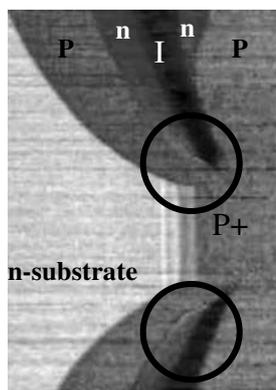


Figure2: Carrier profile by SSRM of the InP-laser (the regions marked with circles are discussed in the text)

SCM is used to study carrier profiles of these regions when the devices are biased. A set of SCM measurements are performed on the lower half of this symmetrical structure as a function of applied bias (cfr figure 3). As the bias increases from 0V to 2.0 V. SCM results show a corresponding change in this particular region. The bridge is getting weaker and eventually intercepted when the bias is above a certain value in figure3 (b). Intuitively one can see that more carriers will go through this bridge region under a higher forward bias. The corresponding SCM images provide direct evidence of such a transport. Since small MIS capacitor is actually used in a RF resonant circuitry to form a capacitor sensor in SCM measurements, it works like a varactor whose capacitance varies while applying different bias. As mentioned before, standard SCM detects only the capacitance of majority carriers because only majority carriers can contribute to the changes of the MIS capacitor. However, in the region of junctions or other unneutralized region in an operating device, two kinds of carriers can be pumped to an excessive high level under forward bias condition, which results in the high injection of both carriers. When the sample is forward

biased to a certain level in our experiments, the bridge region with n-p-n junction is under high injection condition, both electrons and holes have high concentrations. As a consequence, both carriers act like majority carriers, which can follow the AC driving voltage in the SCM resonant circuitry. Therefore, the SCM signal is sensitive to both carrier types, which decrease it to a smaller value. The latter is presented as the decreased amplitude of detected signal in the SCM results, which is gray (close to 0V) in our data scale. Compared with the signal on the p-type layer when it is not biased in figure3 (a), SCM shows a decreased signal in the bridge region in figure3 (b) with an eventual interception. As the bias increases to a higher level, we observe the positive signal (white) in the critical region decreases further, and the interception extends further. It is clear that SCM provides a direct observation of carrier profiles in this critical region when the device is operating.

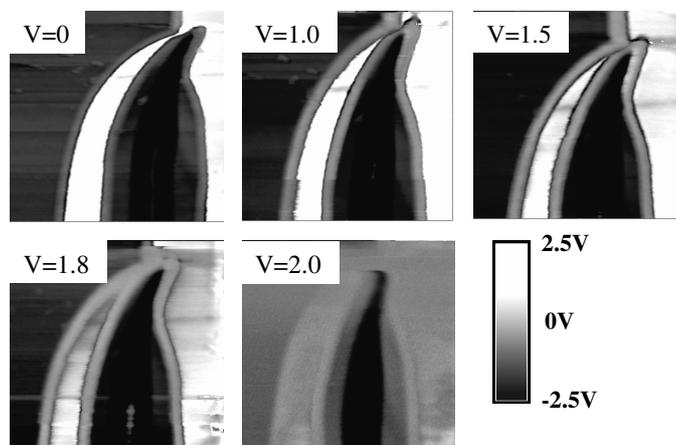


Figure3: a set of SCM results on a laser with different biases: (a) bias=0V (b) bias=1V (c) bias=1.5V (d) bias=1.8V (e) bias=2V

Further work is also performed on the same sample under an even higher drive bias (~3V). SCM begins to show a decreased signal everywhere, which is due to the high injection of both carriers in the device. As a matter of fact, the very high current density in this case introduces physical damage on the device, causing the degradation of device performance. Indeed when the I-V curve of this device after stressing, with the previous I-V before stressing (figure4) drastic differences can be seen. For the stressed device the current substantially increases when the forward bias is above a threshold value (~0.8 V). It is clear that the excessive high drive voltage causes the degradation in its performance, which seems like a broader current channel in this structure.

Since the SCM reveals free carriers profile under operating condition in the previous measurements, we use this technique again to probe this damaged device after a

high drive voltage. Another set of SCM measurements is performed to compare with the previous set of SCM. It is interesting to observe a difference between them. Before the bias exceeds the threshold value at around 0.8 V, the two arms in the SCM image in figure 5 (a), (b) and (c) present symmetrical profiles, which is also similar with the previous measured results on the lower arm region in figure3. However, when the bias is above the threshold, an asymmetrical behavior of these two arms is seen. More precisely, the lower arm presents a decreased signal in the p-type layer like it is in figure3 (d) under high injection condition, compared with its upper counterpart. Remember that there is a substantial increase in transport current through the device at this moment (see the I-V curves in figure4). The difference in the SCM results can be correlated with the I-V characterization in figure4. Since excessive concentrations of both carriers occur due to high injection (the high current in figure4), the SCM-signal in the unneutralized region will decrease and it is easy to understand the decreased signal observed in p-type layer of the lower arm in figure5 (d) and (e).

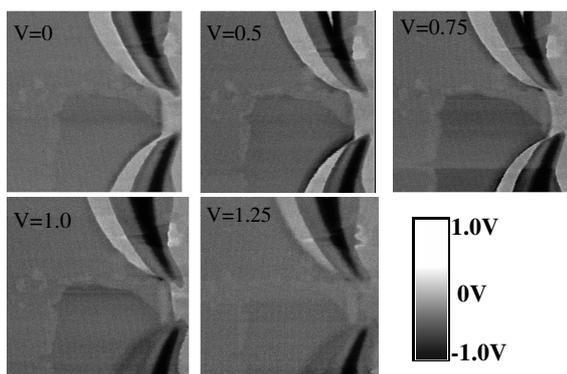


Figure5: SCM results on this damaged device with different biases: (a) bias=0V (b) bias=0.5V (c) bias=0.75V (d) bias=1V (e) bias=1.25V

From above discussion, we can reach two conclusions. Firstly, the degradation of the device performance (more current transport in the device) as seen in the I-V curves, coincides with the SCM observations under the same conditions. Secondly, SCM results denote the region of possible physical damage. The physical damage results in a larger current under a certain bias condition, which can be explained by a larger current channel, including the lateral direction. The SCM results on the lower arm region in figure5 show the position of extra current channel, where both carriers are highly injected when the bias is above the threshold. We can even tell that the extra current channel is a 'broader' InP-based junction, because it has the same threshold voltage as when it is not damaged. Although the determination of the types of physical damage and the reason behind is complicated and out of the capability of SCM measurements, we did see the obvious

evidence of current transport path and are also able to locate the physical damaged region for further evaluation.

CONCLUSIONS

In conclusion, SCM is applied successfully on the active devices, which provides information on the free carrier profiles under the different operating conditions. A qualitative understanding of experiment results can explain the observation in the critical region. Moreover, it is also used to probe the physical damage in device, which proves to be a useful failure analysis tool as well.

REFERENCES

- [1] National Technology Roadmap for Semiconductors, Semiconductor Industry Association, San Jose, CA, USA (1997)
- [2] W. Vandervorst, et al., Invited paper at IEDM2000, San Francisco, CA, USA (2000)
- [3] C. C. Williams et al., Appl. Phys. Lett. 55, 203 (1989)
- [4] C. C. Williams et al., J. Vac. Sci. Technol. A8, 895 (1990)
- [5] S. Anand, et al., Proc. of IPRM'99 Davos, USA (1999)
- [6] P. De. Wolf, et al., J. Vac. Sci. Technol. B16, 335 (1998)

ACRONYMS

SCM: Scanning Capacitance Microscopy
 MIS: Metal Insulator Semiconductor
 AC: Alternative Current
 RF: Radio Frequency
 2D: Two Dimensional
 VLSI: Very Large Scale Integration
 SSRM: Scanning Spreading Resistance Microscopy
 I-V: Current-Voltage