Cryogenic Temperature Nanoscopic Voltage Profiling of Operating Teraherz Quantum Cascade Laser Devices

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ABSTRACT

A nanoscopic probing technique to measure voltage drop across an operating device in cryogenic temperature conditions has been developed and established. The cross section surface of the terahertz (THz) quantum cascade laser (QCL) is profiled to resolve the voltage distribution at nanometer scales. The electric field distribution across the active region of the device has been attained under lasing conditions.

Keywords: nanoscopic probing, atomic force microscope, scanning voltage microscopy, terahertz, quantum cascade lasers.

1 INTRODUCTION

With the advent of nanodevices, technology is being developed to image and observe nanoscale phenomenon occuring in these devices. Contact mode measurments with an atomic force microscope (AFM) has been a well known surface analysis technique [1]. Scanning spreading resistance microscopy (SSRM), scanning capacitance microscopy (SCM) and scanning voltage microscopy (SVM) are some of the advanced measurment techniques developed on the AFM system [2-4]. SSRM and SCM measuremnts has been performed on various semiconductor devices to image high resolution quantum structures while profile and analyse carrier concentrations in the device [2, 5-7]. SVM is the most advanced technique of the AFM-based methods that can non-destructively image the quantum structures on the nanometer scale and can be used to resolve and measure inner workings such as potential profiles, electric fields and their carrier distribution in operating nanodevices [4].

Terahertz (THz) quantum cascade laser (QCL) was first invented in 2002 [8]. Since then, the last decade has witnessed enormous progress in development of these devices. A variety of THz QCLs have been developed with different quantum active region designs including chirped superlattice (CSL), bound-to-continuum (BTC), resonant-phonon (RP) and indirect-pumping (IDP) schemes [9-11]. Improving device performance has always been the goal, explored not only through optimized active region design, but also with innovative waveguide engineering, high-quality molecular beam epitaxy growth and advanced device fabrication techniques. The maximum lasing temperature of THz QCLs has significantly improved since its invention to ~200 K in pulse mode and 117 K in cw mode of operation [12,13]. Despite all these advancements, all reported THz QCLs lase only at cryogenic temperatures, thus lies the major question of why quantum nanodevices cannot operate at room temperature. Probing an active THz QCL to image and observe internal dynamics will reveal the funadamental properties such as charge transport and electric field that play a key role in obstructing the device to operate at room temperature. Due to cryogenic temperature operation of the device, the THz QCL characterization is limited to conventional electrical and optical characterizations such as light-current voltage (LIV) and spectrum measurements [11-13]. THz QCL characterization techniques are limited to input/output behaviors or static physical details. Internal nanoscopic profiles and external macroscopic performance measures have not yet been linked through experimental observation, mainly due to the cryogenic operating conditions of the device. Thus, there was an inability to directly and quantitatively outline electric potentials across quantum cascade modules, preventing the identification of key mechanisms responsible for the sub-par performance.

In this work, we report the development and establishment of a cryogenic nanoscopic probing technique on the AFM system. The intention for this technique is to perform votlage profiling of operating nanodevices and thus be able to extract internal dynamics at cryogenic temperatures. As the measurment can be performed at cryogenic temperatures, the technique is used to probe the inner workings of a lasing THz QCL device. This technique is the only known non-destructive technique to perform voltage profiling of the device, which could lead to imaging the electric field profile and carrier distribution profile in operating devices.

2 EXPERIMENT

Figure 1 shows the schematic experimental setup of the

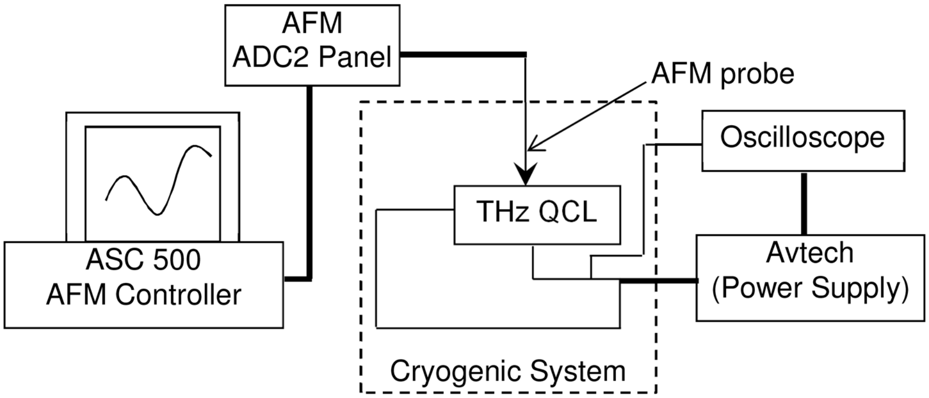

Figure 1. Schematic of cryogenic nanoscopic probing experimental set-up for voltage profile measurement.

cryogenic temperature SVM measurement. A THz QCL device, sample V962 [14], was mounted in a commercially available AFM system (Attocube AFM) that can operate at cryogenic temperatures. The SVM experimental setup is quite similar to the setup used by Ban et al. [2,4,15] for voltage profiling of buried heterostructure (BH) laser devices, except the customized AFM system that satisifies the special requirements for of cryogenic temperature operation [16]. A diamond-coated conductive cantilever probe from Bruker with spring constant = 42 N/m, model no. DDESP-10, is used for the SVM measurements. As shown in Figure 1, the sample is mounted on the AFM system and connected to an external circuitry to perform SVM measurements while the cantilever probe detects voltage signals over the cross-section of the cleaved facet of the laser. The measured voltage data is directly fed back into the acquisition system with the ADC2 Panel and is recorded. The tip used for the measurement has a radius of ~20 nm,however, the scanned image resolves details within ~6-10 nm variations, due to tip's high spatial resolution,.

The THz QCL device was made to operate at a cryogenic temperature of 77 K and all measurements are performed using liquid nitrogen at the cryogenic temperature condition. Bias is applied to the sample by a Avtech pulse generator, while the measured device current and bias are monitored by an oscilloscope. Current-voltage charcteristics obtained from measurements and simulations by Razavipour et al. [14] demonstrate that a current plateau region (constant current with increase in applied bias) has been observed to occur between 6.2 V and 14.9 V of device bias, corresponding to an internal electric field of 6.2 kV/cm and 14.9 kV/cm, respectively. Cryogenic temperature SVM is employed to investigate the internal dynamics of the device in this current plateau region.

3 RESULTS AND DISCUSSION

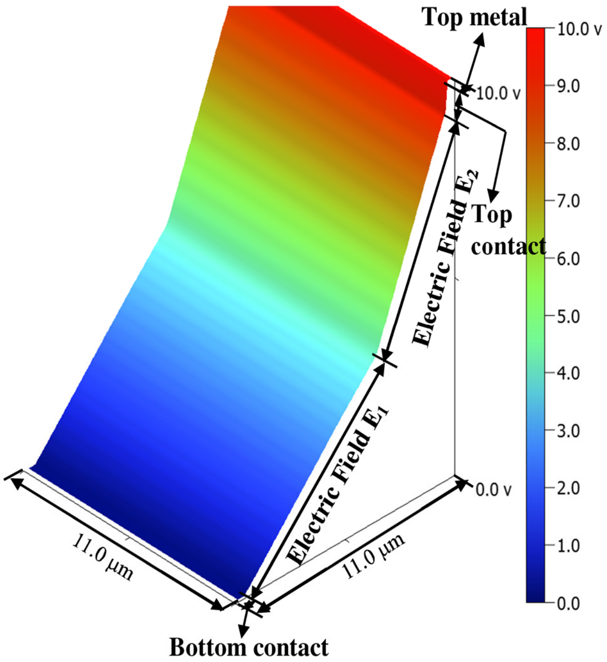

Figure 2. The nano-surface scanned image of 11×11 μm^2 area of a two-dimentional potential profile across the 10 µm active region of a THz QCL device, V962, at 77 K under applied bias of 10 V. It shows two electric field domains (E_1 and E_2).

Nanoscopic measurements are performed at a cryogenic temperature of 77 K on V962 THz QCL device. A two-dimensional (2D) mapping of voltage profile of the sample surface across the nanodevice for 11 × 11 μm^2 is imaged and generated as shown in Figure 2. This measurement is performed at an applied bias of 10 V on top of the device. The measured image distinctly resolves the different sections of the device structure such as the top metal, top and bottom high doped contact layer and the 10 µm thick active region of the device. The 10 V bias applied to the device is known to be in the current plateau region as per the IV characteristics achieved both from simulations and measurements. From this measurment in Figure 2 coexistance of two electric fields is observed in the active region of the device and labelled as E_1 and E_2. Thus formation of electric field domain (EFD) in the device is confirmed. EFDs are major threats for QCL nanodevices and are known to degrade device performance and in some cases renders the devcice inoperable.

Cryogenic temperature nano-surface profiling of operating THz QCL is executed for different applied biases. One-dimensional (1D) section analysis of the 2D SVM generated voltage profiles images across the device is achieved and is presented in Figure 3. Existence of two electric fields E_1= 6.19 kV/cm and E_2= 14.91 kV/cm is observed in the active region section for all applied biases in the current plateau region of the IV characteristics (8-14 V). This clearly implies the existance of EFDs in the active region of the device. The SVM voltage profiles at low applied biases till 6 V and for biases from 16 V to 20 V on top of the device are seen to vary linearly across the active region in Figure 3, thus indicating that when device is not biased in the current palteau region of operation only one electric field exists. Also from Figure 3, a noticeable amount of voltage drop is observed at the metal-semiconductor like Schottky contact. So from this cryogenic temperature nanoscopic voltage profiling measurement, the formation of EFDs are observed thus giving a clear indication about the possible device degradation issues that exists in the THz QCL device under operation, especially in the current plateau region of operation. These device threats needs to be dealt with in future THz QCL designs to achieve enhanced device performance.

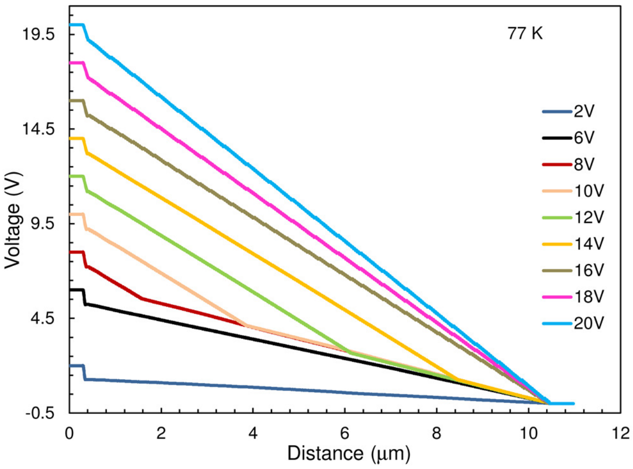

Figure 3. One dimentional (1D) section analysis of the voltage profile across the active region of the V962 device at applied device biases of 2 V-20 V at 77 K. The figure clearly shows existence of two electric fields E_1 and E_2 for current plateau region (8-14 V).

Cryogenic temperature SVM scanning is also performed by zooming in from the top metal to the active region section of the device. Figure 4 presents the 2D zoomed-in scan executed across 500 × 500 nm^2 area that resolves the voltage variation from the top metal contact through high doped semiconductor layer to the active region. The image focusses on the Schottky like contact formed with the metal and the high doped semiconductor at 20 V applied bias on top of the devcie. The SVM measurement revealed the top metal, the n$^+$ GaAs (high doped) layer, and the active region portion in the 500 nm lateral distance of the device. In this Schottky like contact a drop of ~0.805 V is observed. The high spatial resolution of the nano surface profiling was able to resolve the delta doping layer present in each module as per the design structure of the THz QCL device, thus resolving individual module of thicknes. The active region portion of 317 nm is seen in the 2D image of Figure 4, over which 8 lines of delta doped layer are resolved, representing 8 quantum cascade modules in the region equally spaced at ~39 nm. This demonstrate the high spatial resolution achievable with this cryogenic temperature scanning voltage microscopy.

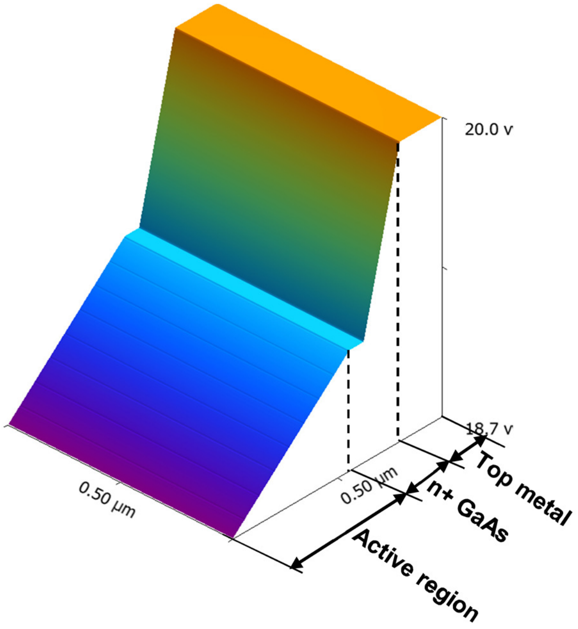

Figure 4. The 2D nanoscopic scanned voltage profile image of 500 × 500 nm^2 area zooming the Schottky like contact on THz QCL at 77 K under applied bias of 20 V.

Scanning is also performed at different applied biases for zoomed-in area as presented in Figure 4. 1D section analysis of these scans are achieved and the voltage drop due to Schottky like contact for different applied biases are measured. The voltage drop in this Schottky like contact is observed and calculated for each applied bias. This calculated voltage drop for different biases at the metal-semiconductor junction is presented in Figure 5. It is observed from Figure 5 that with increase in applied bias on the device the Schottky drop voltage also increases, though it becomes stable and saturates in the current plateau region of operation, this is directly attributed to stable current in this region of operation. An increase in voltage drop across the Schottky like contact is observed at low bias and also in the lasing threshold bias between 16 V and 20 V on top of the device, which can be attributed to the increase of device current over these bias ranges. The measured votlage drop (~0.8 V) across the Schottky like contact is fairly in agreement with the expected value that were obtained from other methods[11, 14].

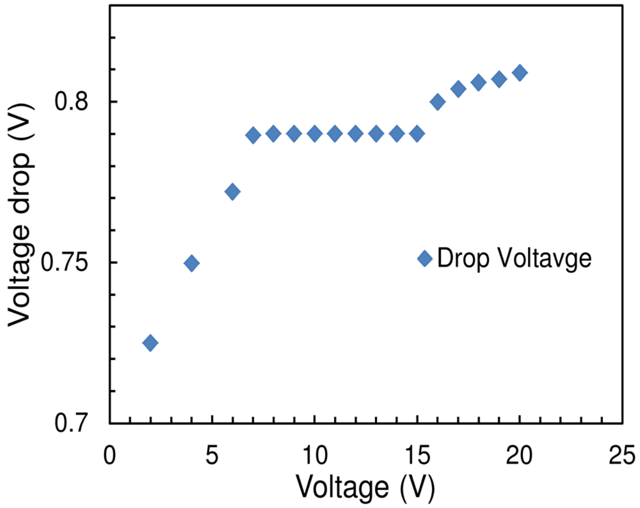

Figure 4. Voltage drop across the Schottky like contact of V962 THz QCL device at 77 K for applied device biases of 2V-20 V.

4 CONCLUSION

A cryogenic temperature nanoscopic voltage profiling measurement technique was established and SVM is carried out on the THz QCL device V962. The voltage profile across the active region and the Schottky like contact is resolved. Coexistence of two electric fields ~6.21 kV/cm and ~14.90 kV/cm is observed from the voltage profiling of the active region in the current plateau section of the applied bias. Thus signifying formation of the electric field domian in the active region of the device, which are known to be major threats in operating nano quantum cascade devices. These threats needs to be minimized in future THz QCL deisgns for enhanced device performance. This cryogenic temperature SVM measurement technique developed can thus characterize voltage and current related issues or threats on operating nanodevices and is thus a major develoment with significant and formidable advancement in the area of nanotechnology.

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