

First Measurements of a Microwave Frequency Comb with a Semiconductor Sample in a Scanning Tunneling Microscope

Chad Rhoades, Member, Joel Rasmussen, Member, Patrick H. Bowles,
Mark J. Hagmann, Senior Member, and Dmitry A. Yarotski.

Abstract—The first two harmonics of a microwave frequency comb (MFC) were measured at a probe which must be within 1 mm of the tunneling junction at the surface of a semiconductor as the sample electrode in a scanning tunneling microscope. The MFC was generated using a passively mode-locked Ti:Sapphire laser with GaN, but lasers with lower photon energy would be required with silicon. The attenuation of the MFC is primarily caused by the spreading resistance in a sub-nm spot at the tunneling junction. Thus, the measured attenuation could be used to determine the carrier density at this spot as an extension of scanning spreading resistance microscopy (SSRM). We anticipate that this effect will enable new nondestructive methods for sub-nm carrier profiling of semiconductors.

Index Terms—Scanning probe microscopy, scanning tunneling microscope, microwave frequency comb, carrier profiling, scanning spreading resistance microscopy

I. INTRODUCTION

WE have previously generated a microwave frequency comb (MFC), with hundreds of harmonics, by focusing a mode-locked ultrafast laser on the tunneling junction of a scanning tunneling microscope (STM) with a metallic sample [1]. Optical rectification creates a regular sequence of pulses, superimposed on the dc tunneling current, which are efficiently transferred by a metallic sample to a bias-T in the sample circuit of the STM. However, with semiconductor samples our simulations, and now our measurements, show the MFC must be measured within 1 mm of the tunneling junction because of the attenuation and dispersion in the carrier transport. By analogy with metal-insulator-metal (MIM) and metal-insulator-semiconductor (MIS) diodes, the effects with metal samples may lead to new nanoscale terahertz devices while the effects with semiconductors may lead to a new tool for nanoscale surface science [2].

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C. Rhoades is with Brigham Young University, Provo, UT 84602, USA (email: carhoades@byu.net).

J. Rasmussen is with Brigham Young University, Provo, UT 84602, USA (email: JoelRasmussen@gmail.com).

P. H. Bowles and M. J. Hagmann are with NewPath Research L.L.C., Salt Lake City, UT 84115, USA (email: newpathresearch@gmail.com).

D. A. Yarotski is with Los Alamos National Laboratory, Los Alamos, NM 87545, USA (email: dzmitry@lanl.gov).

II. APPARATUS AND METHODS

The MFC was generated by focusing a 15 fs pulse train from a Kerr-lens passively mode-locked Ti:Sapphire laser (CompactPro, Femtolasers) to a 100 μm spot at the tunneling junction of a commercial STM (UHV700, RHK Technology). The laser has a pulse repetition frequency (PRF) of 74.254 MHz and an average power of 60 mW. Measurements were made in vacuum at a working pressure of 2×10^{-9} Torr with tungsten tips and in air using Pt-Ir tips. An NI PXIe-5668R High-Performance VSA & Spectrum Analyzer was used to measure the MFC. This instrument operates from 20 Hz to 26.5 GHz with a noise floor of -166 dBm/Hz and it was interfaced with LabVIEW programming to enable rapid acquisition and storage of the data. A wide-bandgap semiconductor, n-GaN, was chosen to avoid forming electron-hole pairs with the laser which would create surge currents that interfere with the measurements [3]. The free-standing single crystal of intrinsic n-GaN has a carrier concentration of approximately $10^{16}/\text{m}^3$ and it was oriented so the tunneling junction was at the (0001) surface.

III. INITIAL MEASUREMENTS WITH PHOTODIODE

The first measurements were made using a Thor Labs DET 210 high-speed silicon PIN photodetector in place of the tunneling junction as a test of the measurement system.

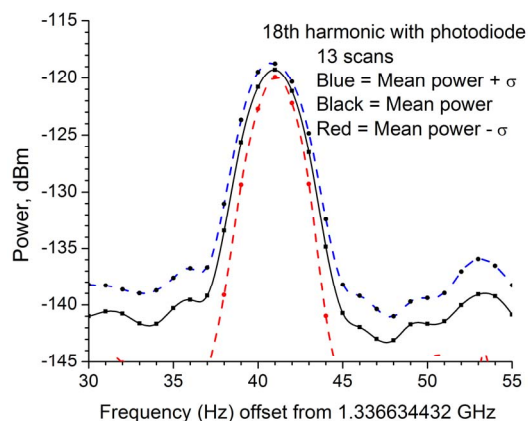


Fig. 1. Power at the 18th harmonic vs. offset frequency for the microwave frequency comb generated with a high-speed silicon PIN photodetector.

Figure 1 shows the measured power as a function of the frequency at the 18th harmonic, which is at 18 times the pulse repetition frequency of the laser, or 1.337 GHz. Note that an offset is used for the abscissa because the linewidth is a small fraction of the center frequency. The apparent linewidth of the harmonic (full-width at half height or FWHH) is 2.7 Hz in this figure. The spectrum analyzer shows the convolution of each spectral line with the resolution bandwidth (RBW = 2 Hz) of the instrument so the actual linewidth is probably sub-Hz. The upper and lower dashed curves in Fig. 1. represent the mean plus and minus one standard deviation, respectively, using the data from 13 consecutive scans. In this figure the ratio of the standard deviation to the mean is 0.146 at the peak.

IV. MEASUREMENTS WITH THE SEMICONDUCTOR

Figures 2 through 5 show the measured microwave power as a function of the frequency offset where the STM sample is a $3 \times 3 \times 0.5$ mm slab from an n-type gallium nitride wafer. The semiconductor had a bias of -9 V relative to the tip for a forward-biased tunneling junction. The dc tunneling current was 1 μ A, the RBW was 2 Hz, and the laser had an average power of 60 mW. Each of these four figures shows the power at the specified harmonic based on 24 consecutive scans. Figures 4 and 5 are magnified with error bars having upper and lower limits corresponding to the mean plus and minus one standard deviation from the 24 scans.

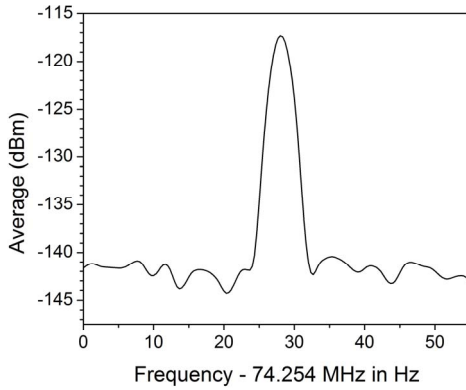


Fig. 2. Average power in the first harmonic vs. offset frequency with the semiconductor as the sample in the scanning tunneling microscope.

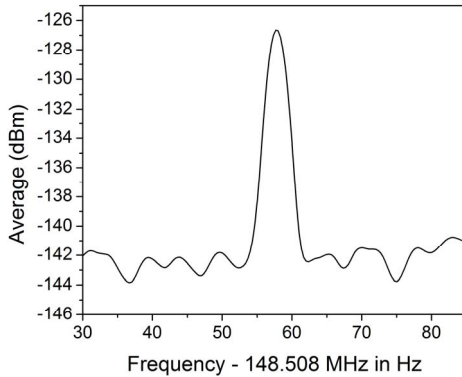


Fig. 3. Average power in the second harmonic vs. offset frequency with the semiconductor as the sample in the scanning tunneling microscope.

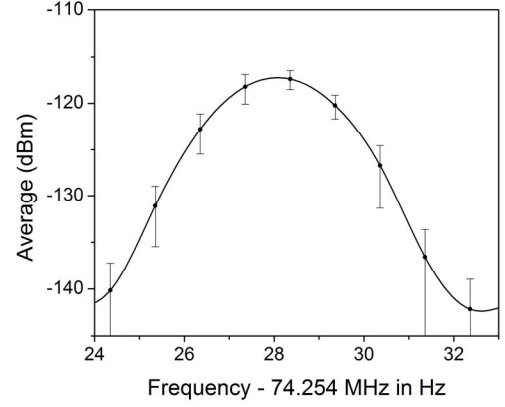


Fig. 4. Average power in the first harmonic vs. offset frequency expanded with error bars for the semiconductor in a scanning tunneling microscope.

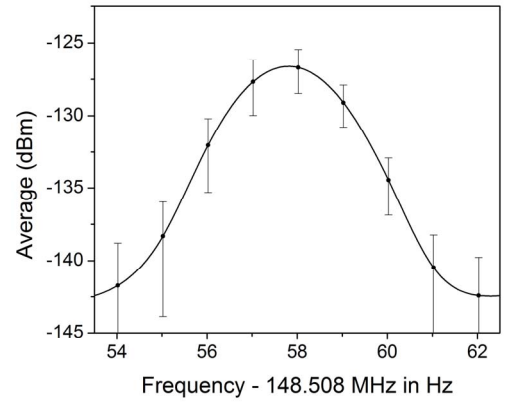


Fig. 5. Average power in the second harmonic vs. offset frequency expanded with error bars for the semiconductor in a scanning tunneling microscope.

Figures 2 through 5 show that that the apparent linewidth at both the first and second harmonics is 2.6 Hz, which is consistent with the value that is seen with the photodetector in Fig. 1. Again, the actual linewidth is probably sub-Hz. Earlier measurements using an RBW of 1 Hz showed an apparent linewidth of approximately 1 Hz from the 1st through the 200th harmonic at 14.85 GHz when using a gold sample instead of a semiconductor [1].

V. PREPARATION OF THE SEMICONDUCTOR

Because our simulations show that it is necessary to make the measurements of the microwave frequency comb within 1 mm of the tunneling junction it is necessary to use a probe to make a fine contact on the semiconductor. One possibility that we could not pursue at this time would be to have a second tunneling junction.

Initially we were concerned that optical rectification could take place at the contact between a wire and the semiconductor. Thus, we used the Al/Ti bilayer metallization scheme [4] with a 5 nm thickness of titanium covered by a 100 nm layer of aluminum, where each layer has a common width of 100 μ m. The system was assembled and pumped but no procedure was available to clean the sample assembly in vacuum. Thus, while we were successful in obtaining a dc tunneling current the MFC was not stable. Even under these

conditions, since each scan took less than 1 second we have data files in which the first and second harmonic were measured simultaneously over several consecutive scans.

Our second approach, which was used in all of the reported data, was to clean the gallium nitride in HF, and then transfer the mounted sample to the STM. A fine gold wire (8 mm long, 0.3 mm dia.) was used as the probe in contact with the surface of the semiconductor and this wire was attached to the sample with an indium coating at the tip. Then, under UHV, we were able to obtain a stable dc tunneling current and measure the microwave frequency comb. We note that the cleaned sample was exposed to the atmosphere for more than one hour before the system was pumped so there is a possibility that the use of vacuum was not necessary.

VI. ANALYSIS OF THE SEMICONDUCTOR MEASUREMENTS

Figures 2 to 5 show that for a semiconductor the MFC has a power at the second harmonic that is 9 dB below that at the fundamental. By contrast, earlier data for metallic samples [1] are consistent with a simple model consisting of a high-frequency constant-current source in the tunneling junction that is shunted by a capacitance ($C_s = 6.4$ pF) and the spectrum analyzer ($R_L = 50 \Omega$) in parallel. Thus, Eq. (1) shows that in those measurements the 2nd harmonic had 94% of the power at the fundamental, and the power at the n th harmonic varies as $1/n^2$ for a decrease of 6 dB per octave at much higher frequencies.

$$P_n = \frac{P_1 [1 + (2\pi f_1 R_L C_s)^2]}{1 + (2\pi n f_1 R_L C_s)^2} \quad (1)$$

Figure 6 is an equivalent circuit that accurately predicts the frequency response of the first and second harmonics of the MFC with a semiconductor having a grounded base. Points P_1 and P_2 represent the tunneling junction and the probe, respectively, at the semiconductor surface. The spreading resistances R_{S1} and R_{S2} are physically small and close to these two points, each connecting to ground and also forming a series connection between the two points. Capacitance C_{12} is distributed over a greater length of the semiconductor.

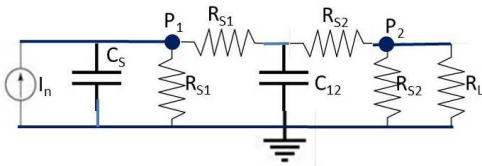


Fig. 6. Equivalent circuit for determining the frequency response of the microwave frequency comb with a grounded semiconductor sample. The grounded semiconductor introduces the spreading resistances R_{S1} and R_{S2} and capacitance C_{12} to form a T-network.

Equation 2 gives the frequency-dependence of the measured power for the model in Fig. 6, where P_n and P_1 are values of the power at the n th harmonic and the fundamental and the parameters A and B are functions of the circuit components.

$$P_n = \frac{P_1 (1 + A + B)}{1 + An^2 + Bn^4} \quad (2)$$

Consider $R_{S1} = 200 \Omega$, $R_{S2} = 44 \Omega$, $R_L = 50 \Omega$, $C_s = 6.4$ pF, and $C_{12} = 22$ pF, which are reasonable values using $R_s = 1/4a$ for the spreading resistance [5], allowing for the dimensions of the semiconductor in C_{12} , with R_L known, and C_s determined previously with metallic samples [1]. With these parameters Eq. (2) predicts that the 2nd, 3rd, 4th, 5th, and 6th harmonics are below the fundamental by 9.0, 15.1, 19.7, 23.4, and 26.5 dB, respectively. This model also predicts that for much higher-order harmonics the power would decrease by 12 dB per octave so it is not surprising that without a preamplifier we were unable to detect beyond the second harmonic.

VII. MEASUREMENTS WITH A GOLD SAMPLE

Measurements were also made with a gold sample to further characterize the system and compare with earlier results obtained with metallic samples [1].

Figure 7 shows the power measured at the 100th harmonic (7.4254 GHz) in the MFC using a 3 mm square gold sample in air. These measurements were made under ambient conditions so a more robust platinum-iridium (Pt-Ir) tip was used to provide greater durability than the tungsten tips used with the semiconductor. The dc tunneling current was 100 nA.

The mean power at each frequency is shown (black solid curve) as well as the mean plus and minus one standard deviation (upper and lower dashed curves). Again, the abscissa in Fig. 7 is offset to show the linewidth which is a small fraction of the center frequency.

Using the NI PXIe-5668R High-Performance VSA & Spectrum Analyzer interfaced with LabVIEW programming for rapid acquisition and storage of the data, it was possible to take all 286 scans in a total elapsed time of 169 seconds. Each scan of 200 points covered a span of 200 Hz, for a resolution of 1 Hz which is seen in Fig. 7, but again the RBW is 2 Hz.

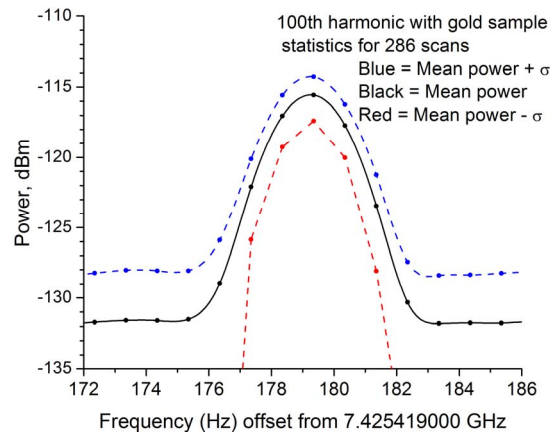


Fig. 7. Power at the 100th harmonic vs. offset frequency for the microwave frequency comb generated with a gold sample.

The statistical results for all 286 scans show an apparent 3dB linewidth (convolution of the linewidth with the RBW = 2 Hz), FWHH = 2.6 Hz in this figure. However, the pulse repetition frequency of the laser has an rms drift rate of 0.2 Hz/s, which causes a drift in the peak of the 100th harmonic of 20 Hz/s. Thus, in the 169 seconds for the 286 scans we would expect a drift of approximately 3.4 kHz rms. Numerically correcting for the drift, by shifting all 286 scans for a common

frequency at the peak, and using a spline function to approximate the wavelength of each, we see linewidth of 2.33 Hz with a standard deviation of 0.219 Hz. This shows that some of the apparent linewidth is caused by drift in the pulse repetition frequency of the laser during the 169 second acquisition time. As noted earlier when presenting the data for the PIN photodetector, the apparent linewidth exceeds the actual linewidth because it is a convolution with the resolution bandwidth which was 2 Hz in all of these measurements. Again, the actual linewidth is probably sub-Hz.

VIII. CONCLUSION

A microwave frequency comb has been measured for the first time with a wide-bandgap semiconductor. There are several ways in which this may lead to high-resolution carrier profiling of semiconductors. For example, the phenomenon of spreading resistance [5], which is implemented for carrier profiling in scanning spreading resistance microscopy (SSRM) [6], shows that most of the attenuation of the MFC occurs within 1 nm of the tunneling junction. Thus, it is possible to define a process for carrier profiling that is similar to SSRM but does not require inserting a nanoscale probe at the point of measurement because that is where a tunneling junction is used to generate the MFC.

When imaging with an STM it is possible to use several different modes including maintaining a constant tip-sample distance or using feedback to maintain a constant current. The constant-current mode, which was used in all of these measurements, requires that the tip-sample distance is varied. However, this requires that the tip-sample distance is changed which changes the capacitance shunting the tunneling junction. We attribute infrequent scan-to-scan jumps in the power at the harmonics of the MFC to these sudden changes in the shunting capacitance. Thus, we suggest that for accurate measurements of the attenuation caused by the spreading resistance it would be necessary to disable the feedback during the short time for each series of scans.

We attribute the unusually narrow linewidth of harmonics in the MFC to the quasi-periodic nature of excitation by a mode-locked laser. This effect has also been demonstrated by measuring a MFC in other systems which do not contain a tunneling junction [3],[7]. It may be surprising that a macroscopic oscillator would have to have a quality factor (Q) greater than 10^{10} to provide a linewidth as narrow as what we have measured in the MFC at frequencies as high as 14.85 GHz [1]. However, it should be recognized that in the limit as ideally periodic excitation is attained, which would require infinite duration, the linewidth approaches zero.

In determining the apparent linewidth for each of the 286 scans with the gold sample it was observed that the scans with the lowest measured power had somewhat smaller linewidths. Statistics was not used to test the significance of this effect. However, it is possible that this variation in the linewidth may correlate with increased fluctuations in the instantaneous value of the dc tunneling current.

It is interesting that the power measured at the 100th harmonic with the gold sample (-116 dBm at 7.425 GHz) was

4 db greater than that measured at the 18th harmonic with the high-speed silicon PIN photodetector (-120 dBm at 1.337 GHz). The generation of the microwave frequency comb with metallic samples in a STM is an extremely fast process that appears to extend to terahertz frequencies [1]. This result is consistent with a large body of previous work by others using point-contact tunneling metal-insulator-metal (MIM) diodes at terahertz and infrared frequencies [8].

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