# Dynamic Electroluminescence Imaging as an "Optical Oscilloscope" Probe

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## Abstract

Dynamic Electroluminescence Imaging (DEI) is a technique used to observe semiconductor devices as they operate. Much like a traditional oscilloscope, the technique delivers waveform information that is useful for assessing the operation of the circuits that comprise a device. It can be thought of as a non-contact "optical oscilloscope probe". The technique has two major advantages over traditional electrical oscilloscope probing. The technique is noninvasive and has a theoretical bandwidth approaching 100 GHz. This means that very fast signals can be observed without unduly loading or otherwise interfering with the circuitry under test. Moreover, the characterization of signals at individual nodes along a signal path allows problems that arise from intervening interconnects and transmission lines to be identified. This paper will show several examples of the radio frequency (RF) measurement capabilities of this technique that have been demonstrated in our laboratory.

## Introduction

DEI is an optical technique wherein light emitted from operating semiconductor devices is collected and time correlated with an AC electrical signal that is exercising the circuit. Light collection is performed with a conventional microscope and imaged onto the photocathode of a Mepsicron II™ imaging photomultiplier tube with control electronics configured for single photon counting. The passage of an electron pulse through the tube is used to generate an external timing pulse for time correlation measurements.

The background count rate or dark count rate of the Mepsicron II™ detector is better than 0.0001 counts per second per image pixel. The quantum efficiency of the photocathode is generally better than 5% throughout the visible spectrum (VIS) and well into the near infrared (NIR). The system is capable of imaging electroluminescent radiation arriving at the photocathode at a rate of less than 1 photon per pixel every ten seconds.

Figure 1 shows the DEI measurement system information flow topology.

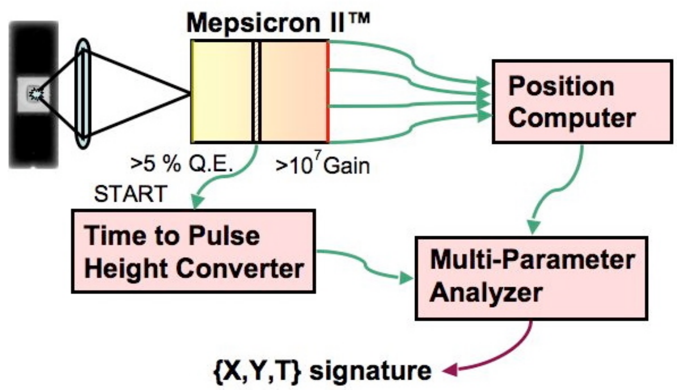


*Figure 1: The DEI measurement system.*

McMullen et al. first described the DEI time correlated imaging technique in 1987 [1]. This method, when applied to logic circuitry, was further developed at IBM and given the acronym PICA, for Picosecond Imaging Circuit Analysis. An excellent review of this technique can be found in the fifth edition of the Microelectronics Failure Analysis Desk Reference [2]. More recently, an interesting technique that sacrifices imaging capability for detector speed has been described by Stellari *et al.* [3].

## Experimental

Three parts were tested to demonstrate the ability of the DEI technique to non-invasively measure RF waveforms. These were a discrete red light emitting diode (LED), a discrete AlGaAs/GaAs HBT device, and an integrated AlGaAs/GaAs HBT RF module. These parts each exhibit strong electroluminescence in the near infrared (NIR) portion of the electromagnetic spectrum that lies within the range of sensitivity of the Mepsicron II™ detector. Indeed, since DEI is a photon counting technique, the light from each of these had to be attenuated by several orders of magnitude in order to reduce the photon arrival rate to within the bandwidth of the time correlated photon detection system. This illustrates the sensitivity of this detector.

**The Red LED**

The LED was forward biased at 1.6 V and a 900MHz sinusoidal signal from a 50 Ω signal generator was coupled to it through a 0.1 µF capacitor. The signal generator power level was configured to deliver -15.0 dBm into a 50 ohm load. A 10 MHz reference signal from the signal generator served as a time standard for the measurements.

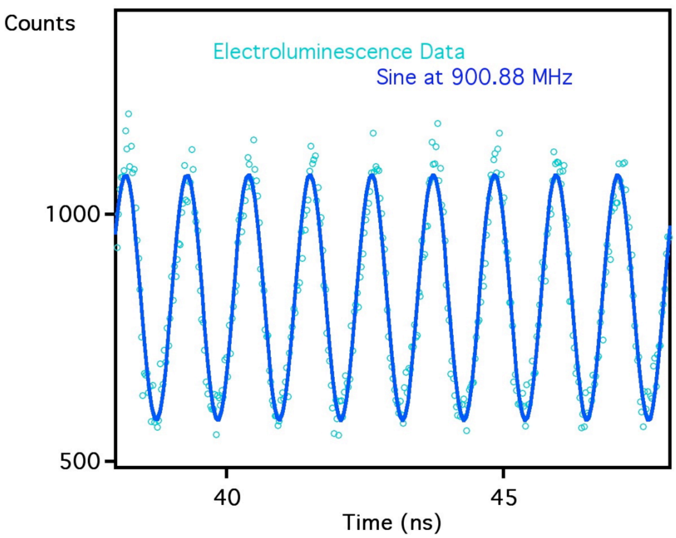


*Figure 2: Electroluminescence data detected from the red LED driven at 900 MHz. The figure shows the measured data as dots, and the fit with a 900.88 MHz sine wave shown as a solid line.*

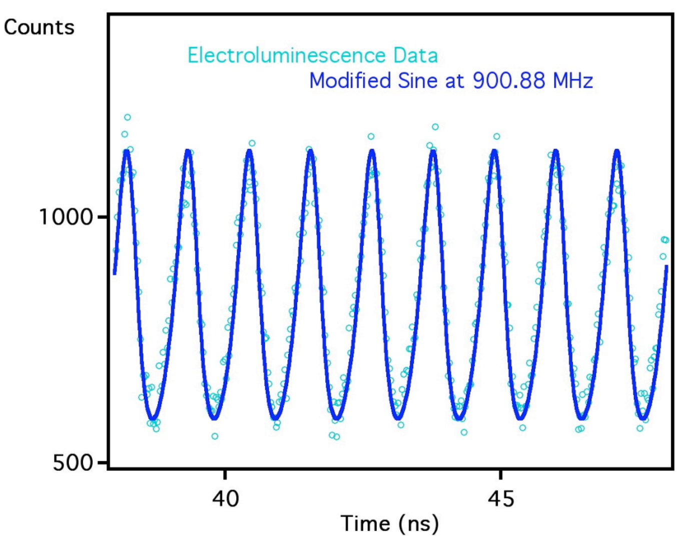


*Figure 3: The LED electroluminescence data of Figure 2 fitted with the modified sinusoid as discussed in the text.*

Figure 2 shows electroluminescence data detected from the red LED. The driving frequency was set at 900 MHz. A sine wave is not a good fit to the data. The peak maxima are sharper than a sinusoid and the data is skewed somewhat in time. This is because the electroluminescence is proportional to the current flowing through the diode. However, the diode current is exponentially related to the bias voltage and only approximately linear in voltage over the range of the small AC signal superimposed on the applied DC bias. This will make the peak current and therefore the peak electroluminescence sharper. The skew is a result of a modulation of the PN junction capacitance by the applied AC signal.

A model that better describes the time-dependence of the electroluminescence features a 900.88 MHz sinusoid with a small exponential pre-factor, leading to sharpening of the electroluminescence peaks and a small sinusoidal phase shift at the same frequency. Figure 3 shows the improved fit of the data that this model provides.

**The AlGaAs/GaAs HBT**

Figure 4 shows the measured DEI image data of the HBT. The device was biased in the linear region of operation with the collector at 0.0 V, the base at -1.0 V and the emitter at -4.0 V through a 1 kΩ resistor. Again, a sinusoidal signal at -15.0 dBm into 50 Ω was coupled to the base through a 0.1 µF capacitor. A 10 MHz reference signal from the signal generator served as a time standard.

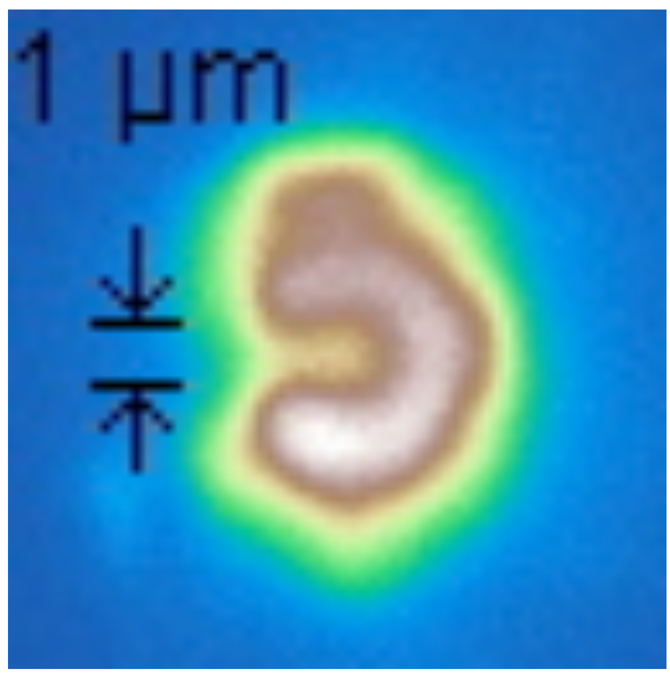


*Figure 4: The DEI image of the AlGaAs/GaAs HBT.*

The detected electroluminescence from the HBT was much easier to interpret, as it showed the same waveform characteristics as the driving signal. The HBT response is linear in this case. This is advantageous, as it means that the electroluminescence from such devices embedded in circuitry can reveal the characteristics of the signal passing through the device exactly.

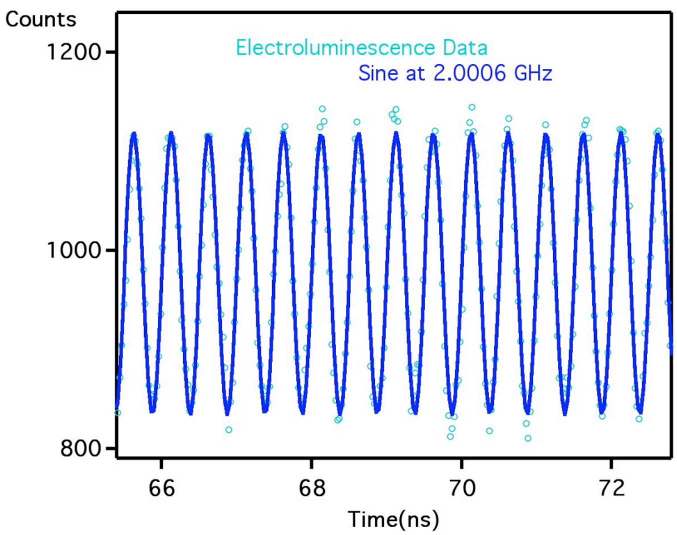


*Figure 5: The AlGaAs/GaAs HBT being driven at 2.00 GHz. The figure shows the measured data as dots and the fit with a 2.0006 GHz sine wave shown as a solid line.*

**The RF Module**

The RF module was a two metal layer AlGaAs/GaAs HBT high power differential distributed amplifier that has been described by Wong et al. [4]. This part was not operating as expected. The failure mode of the device under test (DUT) was low output gain. Figure 6 shows a simplified schematic of the output buffer. The transistors identified as M3 through M6 are in fact lumped transistors. The circuit consists of a differential input gain stage (M1, M2) followed by an emitter follower buffer stage (M3, M4) and finally an output differential gain stage (M5, M6). Depending on whether a logic '1' or a logic '0' is present at the input, the two differential stages will switch completely. Thus current will only flow through one side of the differential pair.

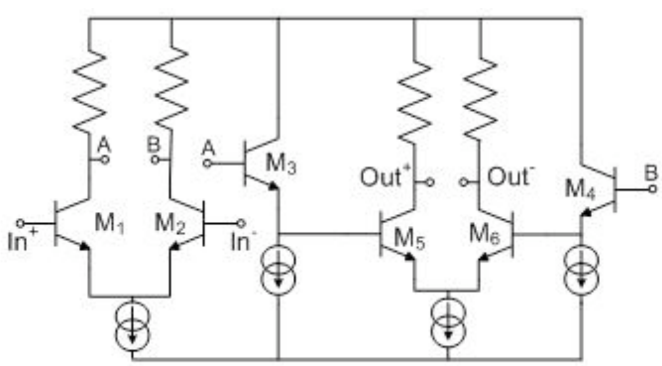


*Figure 6: Simplified schematic of the* high power RF differential distributed amplifier.

Since the device contained only two metal layers, front side imaging was possible. Had more metal layers been present backside imaging would have been preferred. The DUT was exercised continuously with the output of an 8:1 differential serializer driven at 4GHz with a 01h parallel input bit pattern. This input will produce a 500MHz pulse train with each pulse 250ps wide. It was necessary to inject the data continuously, since the photon image and time signature of the DUT must overcome the noise floor of the photon detector and the timing circuitry respectively.

**Input Differential Gain Stage**

Figure 7 shows the luminescence of transistors M1 and M2. Using a Lorentzian curve fit to estimate the peak location and the full width at half maximum (FWHM) from the data, a pulse period of 1.997ns with a pulse width of 247ps was calculated for M1 and a pulse with of 246ps was calculated for M2. Notice in particular that Figure 7 shows that full switching occurs between M1 and M2.

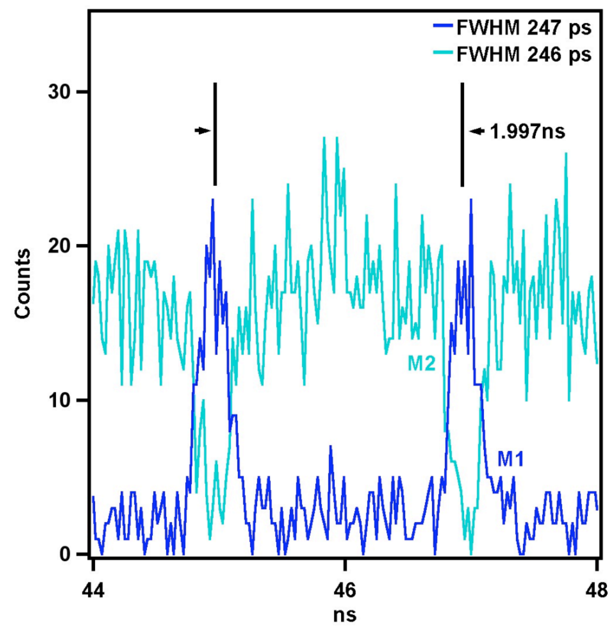


*Figure 7: The electroluminescence waveforms from HBT M1 and M2 of the input differential gain stage.*

**Emitter Follower Buffer Stage**

The emitter follower stage does not fully switch on or off depending on the input data. Rather, the base current is modulated slightly. Figure 8 shows the electroluminescence observed from an HBT in each of M3 and M4. The signal was barely visible above the noise floor. Had a longer acquisition time been chosen, the time signature of these devices would become more apparent. A Fourier transform of the waveforms shown confirmed that there is a significant spectral component at 500MHz.

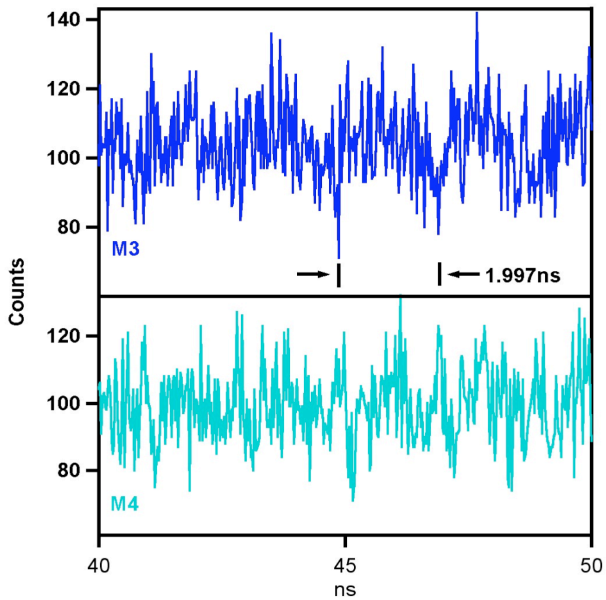


*Figure 8: The electroluminescence waveforms from HBT M3 and M4 of the emitter follower buffer stage.*

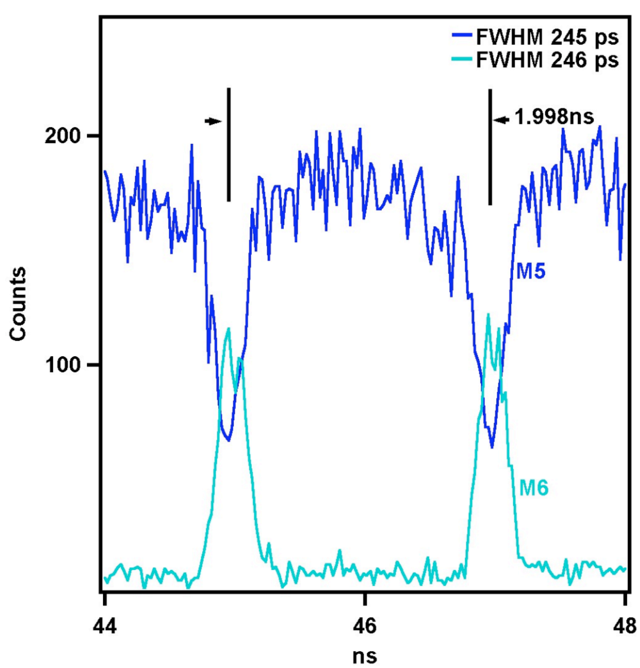


*Figure 9: The luminescence waveforms from HBT M5 and M6 of the output differential gain stage.*

**Output Differential Gain Stage**

Figure 9 shows the luminescence of transistors in each of M5 and M6. Once again, using a Lorentzian curve fit to estimate the peak location and the FWHM, a pulse period of 1.998ns with a pulse width of 245ps was observed for M5 and a pulse width of 246ps was observed for M6. Examining the luminescence waveforms of these devices, it can be seen that the devices do not fully switch since the photon count never falls below 60 counts for M5 and never rises above 115 counts for M6. Since these devices do not fully switch, the final output differential voltage will be smaller than desired.

DEI has thus been shown to be able to localize the failure in this example. The measurements took very little time, and since no physical probing was required the measurements did not interfere in any way with the operation of the circuit.

## Conclusions

DEI is an optical imaging technique that capitalizes on the emission of light that occurs as current flows through semiconductor devices. The examples above demonstrate the ability of DEI to function as a noninvasive "optical oscilloscope". Without loading or otherwise disturbing the semiconductor devices being observed, the DEI method enables the measurement of RF waveforms as they pass through the devices. The degradation of signals passing through circuitry can be identified along the signal path. In this way failures can be identified at individual devices within the circuitry of a DUT. Problems arising as signals progress through connections and transmission lines can also be revealed. The importance of this last point in failure analysis is evident, particularly during diagnosis of a functional failure.

## Acknowledgements

We would like to thank Richard Dudek of NRC for help in mounting the HBT devices.

## References

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[2] Vallett, D., in "Microelectronics Failure Analysis Desk Reference, Fifth Edition", pp. 369-77, ASM International (Materials Park, OH, 2004).

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