SUPERCONDUCTING SINGLE-PHOTON DETECTOR ENABLES TIME-RESOLVED EMISSION TESTING OF LOW-VOLTAGE SCALED ICs

Andrea Bahgat Shehata, Franco Stellari, and Peilin Song
IBM T.J. Watson Research Center, Yorktown Heights, NY
andrea.bahgat@gmail.com
stellari@us.ibm.com, psong@us.ibm.com

TIME-RESOLVED OPTICAL PROBING OF SIGNALS ON SCALED ICs

Notwithstanding the continuous advances in design-for-manufacturing and design-for-test features, the use of noninvasive optical techniques for probing waveforms from internal nodes of integrated circuits (ICs) remains very important for the fast and accurate localization of failures.

Currently, laser voltage probing (LVP)\cite{1} is the most commonly used time-resolved technique. A continuous-wave laser beam is focused through a high-numerical-aperture (NA) optical system to a specific transistor. When a voltage waveform is applied across the transistor under test, there is a change in free-carrier density that alters the local refractive index and the silicon absorbance, thus giving rise to a modulation in the reflected laser light.

“LUCKILY, NOVEL PHOTODETECTORS SUCH AS THE SUPERCONDUCTING SINGLE-PHOTON DETECTOR (SSPD) THAT HAVE BECOME AVAILABLE IN RECENT YEARS HAVE HELPED RETURN THE LIGHT TO THE TRE TECHNIQUE, DUE TO LOWER NOISE (FEW DARK COUNTS PER SECOND) AND BETTER JITTER.”

The small modulation in the light reflected from the structure is detected by a fast photodiode (Fig. 1a). This method is extremely sensitive and has only a modest

\[ \text{(a)} \quad \text{(b)} \]

Fig. 1 Comparison of the two main optical techniques used to detect timing-related faults within an IC. (a) In LVP, a laser is shined toward the device, and the reflected light is modulated by the carriers and detected by a detector. (b) In TRE, NIR photons are spontaneously emitted by the IC and collected by the detector.
linear dependency on circuit voltage. However, the laser may also alter timing characteristics of the device. As device geometries shrink, the number of injected carriers required to affect the operation of the circuit also decreases, thus making it possible to cause catastrophic damage to the device. Furthermore, when multiple switching transistors lie inside the focused laser spot, the acquired signal becomes complex to interpret due to the constructive and destructive contributions. Different transistors modulate the reflected beam with different phase conditions, and so the signal is not strictly additive; in some cases, the modulation may be cancelled out almost completely through two opposing phase conditions. Usually, LVP is used in combination with a laser scanning microscope, allowing the user to test a portion of the chip (laser voltage imaging).

On the other hand, time-resolved emission (TRE), also known as picosecond imaging circuit analysis (PICA), is a truly noninvasive technique, based on the collection of intrinsic near-infrared (NIR) photon emission from CMOS transistor channels (Fig. 1b). This technique allows one to detect both the logic state of the gates and the switching events (Fig. 2). Considering a digital gate, a faint but continuous emission is produced by the leakage current during off-state with the gate grounded and the drain high. No emission is produced when the transistor is in ohmic state with drain and source shorted; a short, bright emission peak is produced during a switching event, because the transistor momentarily undergoes saturation. Contrary to LVP, TRE signals are always additive, meaning that if two different devices are emitting close to each other, the resulting collected waveform will have the signals from both devices. Time-resolved emission measurement of off-state leakage and carrier recombination have led to completely new applications, such as latch-up ignition, power supply noise, slew-rate measurement, self-heating estimation, variability characterization, and so on. However, during the last decade, the use of TRE has been significantly limited by two critical factors: sensitivity (as a combination of detection efficiency, detector noise, and spectral coverage) and time resolution. As the chip supply voltage is reduced, the intrinsic photon emission decreases exponentially, making the use of TRE techniques challenging for low-power ICs. Luckily, novel photodetectors such as the superconducting single-photon detector (SSPD) that have become available in recent years have helped return the light to the TRE technique, due to lower noise (few dark counts per second) and better jitter (approximately 30 ps full width at half-maximum). It must be noted that at the present time, TRE allows one to probe single points in a chip; however, lower acquisition times are needed with better detectors, and raster scanning can be applied to cover at least a small area of the device under test (DUT). Moreover, 2-D detectors are currently being developed, which will enable parallel acquisition.

**SUPERCONDUCTING SINGLE-PHOTON DETECTOR**

An SSPD is a meander made of superconducting material (in this case, NbN shaped in a 9-µm-diameter circle to match the single-mode fiber used to collect the light; Table 1

<table>
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![Figure 2](https://example.com/fig2.png) **Fig. 2** Example of luminescence signal (L) from a simple inverter gate. With TRE, it is possible to retrieve both the logic state of the gate (the gate is leaking when it is off) and when it turns on (in correspondence of the switching emission peak).
Fig. 3 (a) NbN meander, shaped in a 9-µm-diameter circle, that was used for this work. (b) Three-stage closed-cycle cryostat that houses the SSPD. (c) Working principle of the SSPD. The detector is biased at a constant current lower than the critical current. When a photon hits the nanowire, a hotspot is created. The current crowds at the edges, and when it becomes higher than the critical current value, the superconductivity is lost, leading to a voltage pulse that can be detected by external electronics.

LOW-VOLTAGE SENSITIVITY

The typical experimental setup used to acquire TRE waveforms with the SSPD is shown in Fig. 4. A pulse generator provides a clock to the DUT while its spontaneous emission is collected by the high-NA solid immersion lens of a microscope and, through a single-mode fiber, is fed to the SSPD. The delay between each detected photon from the SSPD and the clock synchronization signal is measured by the timing electronics. The cumulative histogram of all the photon arrival times is used to reconstruct the TRE waveform. Note that most of the optical tools (e.g., those from FEI and Hamamatsu) can be retrofitted to perform TRE measurements. The only requirements are a fiber port to connect the SSPD as well as timing electronics to reconstruct the measured waveform.

Figure 5 shows the emission intensity measured at different chip supply voltages from an inverter gate in 32 nm silicon-on-insulator (SOI) technology using two generations of SSPD. The switching emission signal is measured as the amplitude of the switching emission peak in the TRE waveform, while the noise is the standard deviation of the intensity level correspondent to the semiperiod during which the field-effect transistor (FET) is conductive. Figure 5 shows that the measurement noise is limited by the detector noise (dark-count rate, or DCR) for voltages lower than 0.65 V. The second-generation SSPD is characterized by a higher system detection efficiency; as a consequence, both the switching emission
The noise at low voltage is limited by the detector noise, while at high voltage it is limited by the background (i.e., light coming from neighboring devices). The second-generation SSPD yields a better SNR at high voltage due to its improved detection efficiency, but it also has worse performance at low voltage due to its higher DCR. It should be noted that the switching emission peak amplitude strongly depends on the temporal response (i.e., jitter) of the system (detector + electronics): the lower the jitter, the narrower and taller the peak. Therefore, it is crucial to optimize the SSPD front-end electronics. With careful tuning of the main system knobs that are available to the user, it is possible to acquire TRE waveforms in just a few seconds at a nominal supply voltage of 0.9 V and in approximately 20 min at a world record low-supply voltage of only 0.4 V \((\text{Fig. 6})\).

**APPLICATION TO SCALED TECHNOLOGY NODES**

The capabilities of TRE have been demonstrated on scaled technology nodes such as a ring oscillator fabricated in 14 nm FinFET technology. The TRE waveform acquired from one of the inverter stages is shown in Fig. 7. Each minimum-sized transistor has five fins, and the separation between \(n\)FET and \(p\)FET of each inverter is 86 nm.
The frequency of the ring operated at 1 V is 508 MHz, leading to a period of approximately 2 ns. Due to the scaled feature size, light can be collected from both the nFET and pFET in a single measurement, as shown in Fig. 7.

CONCLUSIONS

Notwithstanding the continuous advances of design-for-manufacturing and design-for-test features, time-resolved optical probing techniques remain an indispensable tool to increase the accuracy and speed of fault localization. Novel detectors, such as the SSPD, have become available to return light to TRE techniques that can aid or replace LVP in situations where complete noninvasiveness is necessary. The detector and the technique have been demonstrated for scaled nodes such as 14 nm FinFET SOI and for ultra-low-power supply voltages down to 0.4 V.

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ABOUT THE AUTHORS

Andrea Bahgat Shehata received his B.S., M.S., and Ph.D. degrees (summa cum laude) in electronics engineering from the Politecnico di Milano, Milan, Italy, in 2007, 2009, and 2013, respectively. In 2013 he joined the IBM T.J. Watson Research Center, Yorktown Heights, NY, as a postdoctoral researcher. His current research interests include the development and characterization of new systems for testing very-large-scale integration circuits based on static imaging and time-resolved emission. Dr. Bahgat Shehata worked with low-jitter and high-quantum-efficiency SSPDs, pushing their limits toward record low-voltage applications. He has more than 45 publications. In 2015, Dr. Bahgat Shehata was awarded the Paul F. Forman Team Engineering Excellence Award.

Franco Stellari received M.S. and Ph.D. degrees in electronics engineering from the Politecnico di Milano, Italy, in 1998 and 2002, respectively. He subsequently joined the IBM T.J. Watson Research Center as a postdoctoral researcher, becoming a research staff member in 2004. His major interests are the development and use of new optical methodologies for very-large-scale integration circuit testing and hardware security. He has more than 85 international publications and more than 24 patents. Dr. Stellari has been the recipient of four Best Paper Awards and the Paul F. Forman Team Engineering Excellence Award.

Peilin Song is a Principal Research Staff Member at the IBM T.J. Watson Research Center, where he manages the Circuit Diagnostics and Testing Technology Department. He joined IBM in 1997 and has since worked in the area of design for testability, fault diagnostics, optical testing, and recently hardware security and reliability. Dr. Song has more than 100 publications and holds more than 38 U.S. patents, with several patents pending. In 2004, he won the IEEE Electron Device Society Paul Rappaport Award. Dr. Song is an IEEE Senior Member. He received his Ph.D. in electrical engineering from the University of Rhode Island in 1997.

NOTEWORTHY NEWS

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