Transmission Line Termination

Beyond Design

by Barry Olney, IN-CIRCUIT DESIGN PTY LTD / AUSTRALIA

In a previous column "Beyond Design: Interconnect Impedance," we saw that the impedance of the interconnect is the most critical factor in high-speed PCB design. Unfortunately, the source impedance of a digital IC driver is typically lower than the impedance of the transmission line (10–35 ohms). This is far from the ideal situation for the perfect transfer of energy, and, in most cases, results in reflections and electromagnetic radiation if not addressed.

Whenever a signal meets an impedance variation along a transmission line, there will be a reflection, which can seriously impact signal integrity. By understanding the causes of these reflections and eliminating the source of the mismatch, a design can be engineered with reliable performance. In this month's column, I will look at how to effectively terminate transmission lines.

In an ideal world, the energy emanating from an IC output driver would travel through the PCB transmission line and be totally absorbed by the load. However, if energy is not completely absorbed, then the residual will be reflected back along the interconnect, reaching the original source of energy at the output driver. Reflected energy acts like a standing wave and adds or subtracts to the original signal, causing ringing. Resonance can develop at a signal's fundamental frequency or harmonics resulting in multiple bounces and emission of radiation. This situation only occurs when the round-trip delay of the interconnect exceeds the signal rise time.

Even if the multilayer PCB has been designed with controlled impedance in mind, impedance discontinuities can still occur due to input gate capacitance, branches, stubs, or test pads; variations in dielectric materials; a neck-down in a via field; skew in a differential pair; or a gap in the return signal path. Generally, the reflected noise level should be kept below 10% of the voltage swing, but this depends on the noise budget. In more conservative designs, the noise budget may be as low as 5%.

There are numerous ways to terminate transmission lines, but the most common methods fall into three categories:

1. Series termination
2. End termination
3. Differential pair termination

1. Series Termination

Series termination (aka source termination) is excellent for point-to-point routes—one load per net. It works well for traces that are electrically short and is used to fan out multiple loads radially from a common source (star routed) without affecting other circuits in the network (Figure 1).

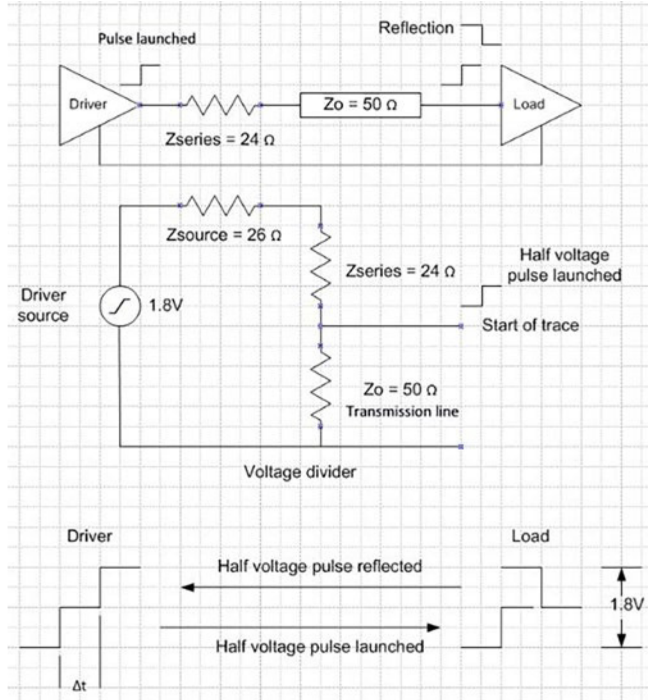


Figure 1: Series termination (back-matching).

Impedance back-matching slows down the rise and fall times and reduces the ringing (over/undershoot) of clock drivers. A pulse is launched from the source, but due to the voltage divider network formed by the source impedance, series terminator, and the transmission line, only half the amplitude appears at the transmission line. As this half voltage pulse reaches the load, it is instantaneously reflected back along the trace. This reflected

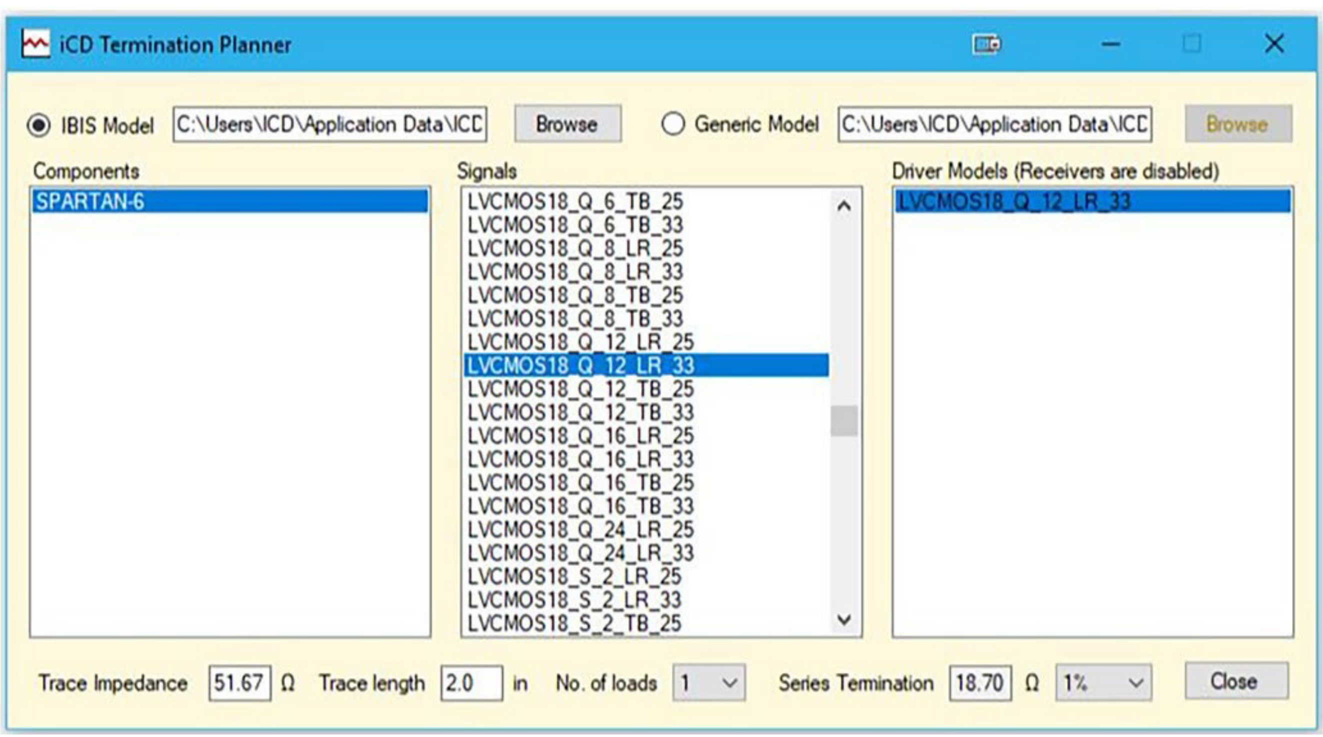


Figure 2: Matching the Spartan 6 driver to the transmission line (iCD Termination Planner).

pulse adds to the initial pulse to form a full voltage wave, so we get the signal we want at the load.

The reflected pulse travels back to the source. When it reaches the series terminator, it sees the series resistor (24 Ω) plus the source impedance (26 Ω) totaling 50 Ω. Since the transmission line is also 50 Ω, there is no discontinuity of impedance; therefore, there will be no reflection. The signal will be totally absorbed by the terminating resistor and the source impedance, preventing further ringing.

A receiver located at the very end of the trace will see an almost perfect signal edge. But a receiver in the middle or near the resistor will first see a 50% signal and then a 100% signal. Because of this, series termination is only used when there is only one receiver/load, and that receiver must be located at the very end of the transmission line.

To determine the value of the series terminator, the source impedance must be extracted from the IBIS model of the driver IC. Subtracting the source impedance from the trace characteristic impedance gives the required series terminator value (Figure 2).

In the previous example, using a 12 mA LVCMOS 1.8V driver of a Spartan 6 FPGA, an 18.7-ohm series resistor is required to match the driver to the 51.67-ohm trace on the outer layer. This is automatically derived from the IV curves of the Spartan 6 IBIS model by the iCD Termination Planner.

Figure 3 illustrates the ringing (red) in an unmatched transmission line. This ringing, which is also represented by over/undershoot (right), is dramatically reduced by terminating the transmission line with an 18.7-ohm series resistor (blue).

2. End Termination

Multi-drop bus topologies require parallel or end termination, which prevents reflections from being formed at the transmission line ends. With DDR3/4 memory devices, for instance, the fly-by address, control and command (ACC) signals should be routed as close as possible to the memory device pins and the parallel termination placed at the end of the line (Figure 4). The resistor values are twice that of the transmission line as they are in parallel from an AC perspective. Short stubs can be used to connect the passing signal to each memory device in sequence, but the longer the stubs, the higher the capacitance. This stub capacitance, along with the parasitic input capacitance of the receiver pin, creates an imperfection in the termination network.

Figure 4 illustrates a typical DDR3 fly-by topology with the termination at the very end of the final load. Also, the passing address signal trace goes directly to the receiver pins with no stub. This is the ideal scenario. In this case, there are no reflections from the termination, which can be seen from the waveforms.

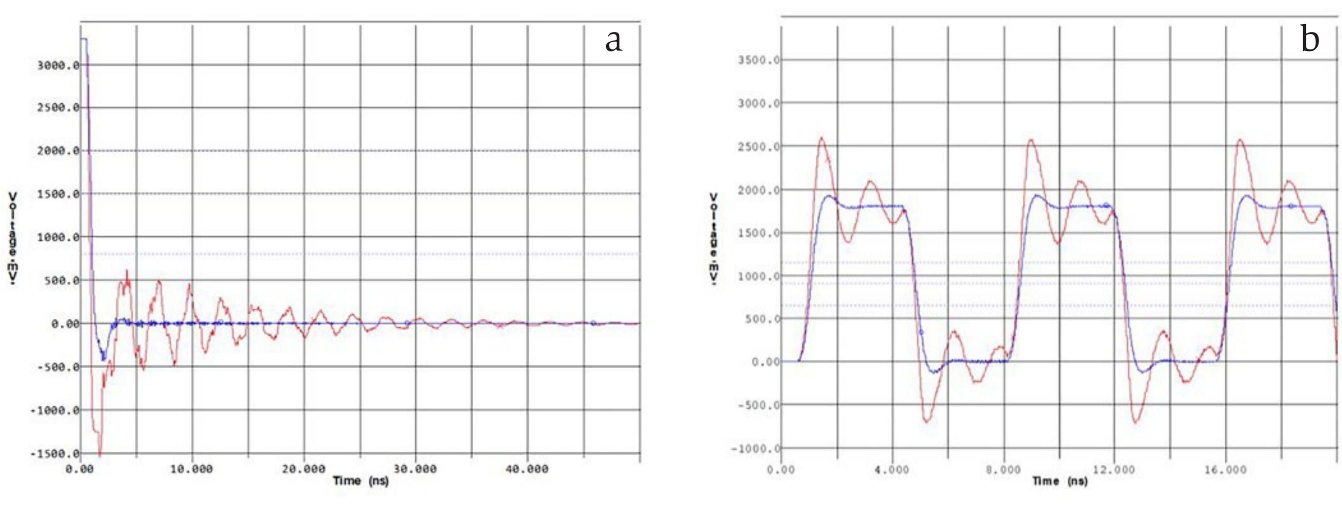


Figure 3a and 3b: Ringing is reduced dramatically by adding a series terminator (simulated in HyperLynx).

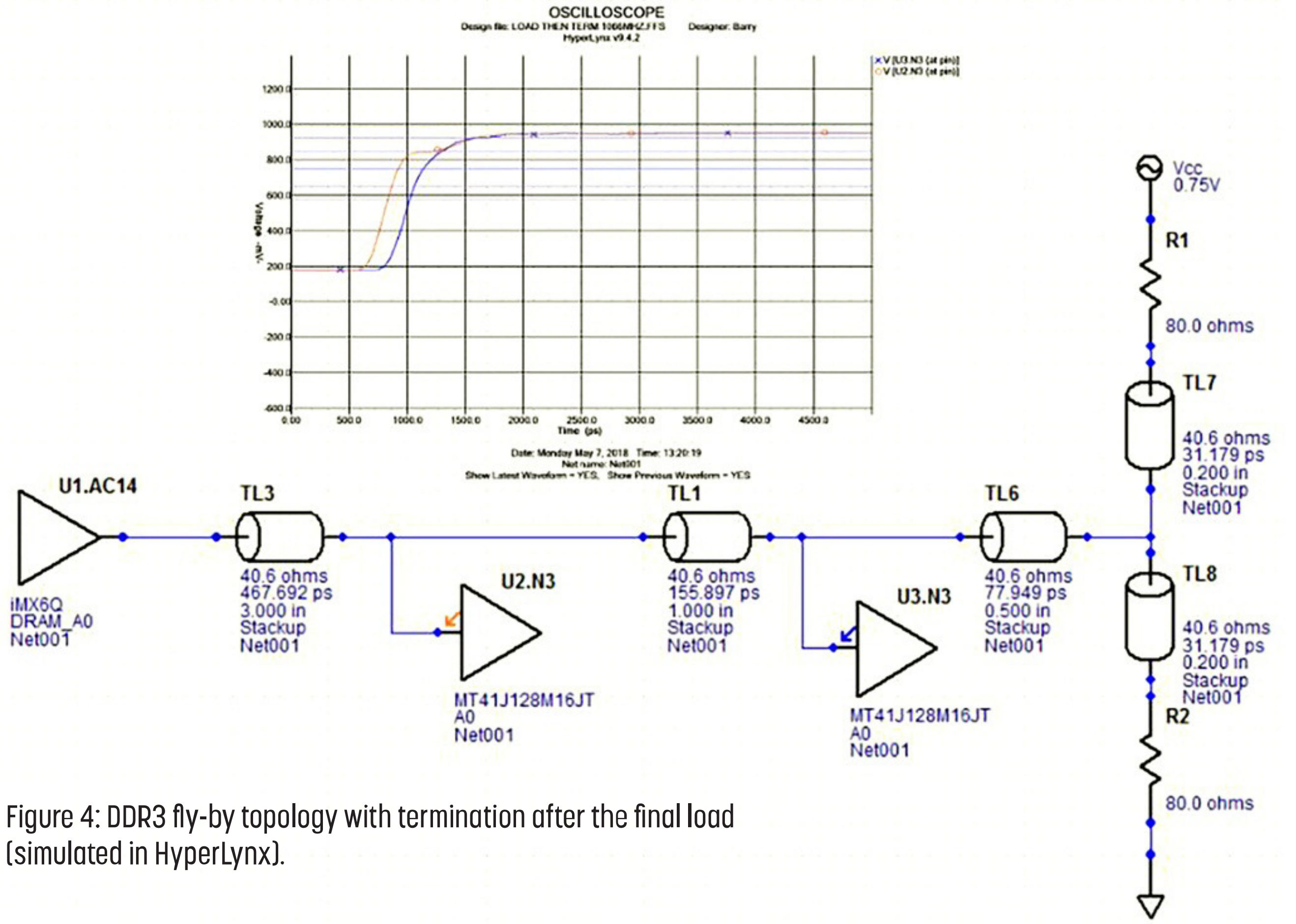


Figure 4: DDR3 fly-by topology with termination after the final load (simulated in HyperLynx).

3. Differential Pair Termination

When a differential signal reaches the open end of a differential pair, it will see a high impedance, and it will be reflected. A common method of reducing these reflections is to place a resistive load at the end of the pair, which matches the differential impedance of the transmission line.

However, the single resistor differential termination (Figure 5a) only terminates the differential mode signal—not the common-mode signal. Any transient common-mode signal moving down the differential pair will see a high impedance at the end of the pair and reflect back to the source. The noise created can be seen at the top and bottom of the eye diagram. The common-mode signal, having the same voltage between the two signals, will not see the termination. Depending on the impedance of the driver, the common-mode signals created will bounce back and forth down the transmission lines. And because the termination resistor never perfectly matches the driver impedance, there is always a fixed offset. Any asymmetry in the differential pair will convert the differential signal into a common-mode signal.

Whereas the differential center tapped termination (Figure 5b) terminates both differential and common-mode signals, note the nice clear eye. It is best used when you have a low impedance driver on a long transmission line. This strategy introduces less DC offset. The DC blocking capacitor is for level adjustment of DC balanced circuits, such as clocks, 8B10B coding, etc.

When Do We Need a Termination?

If the transmission line is short, reflections still occur but will be overwhelmed by the rising or falling edge of the signal and may not pose a problem. But even if the trace is short, termination may still be required if the load is capacitive or highly inductive to prevent ringing. Generally, when the trace length exceeds one-sixth of the electrical length of the rising edge rate, then termination is required. Regardless, it is always a good policy to keep critical signals and return paths as short as possible.

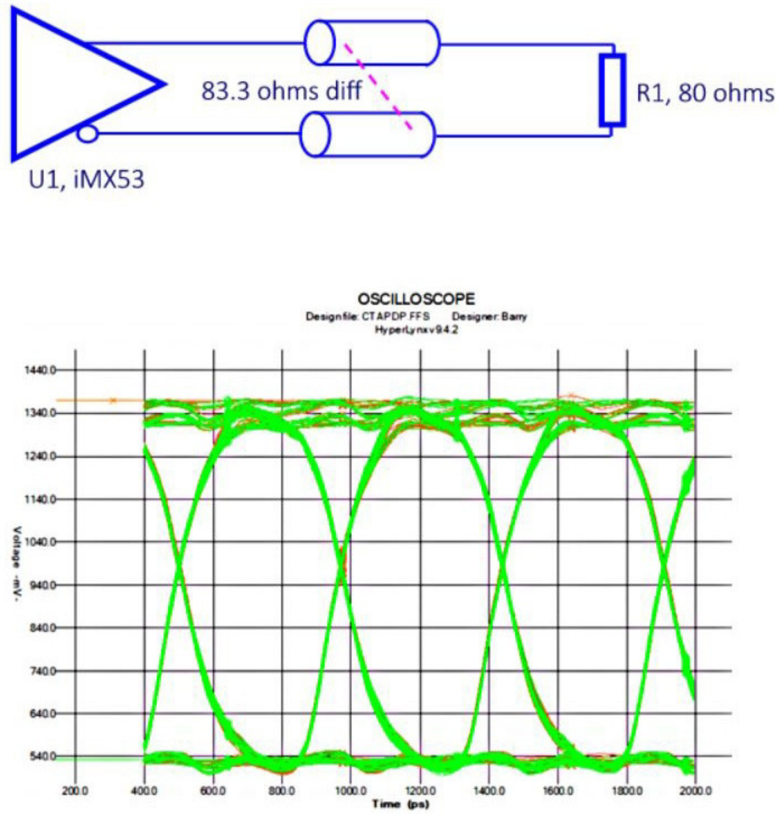


Figure 5(a): Single resistor differential termination.

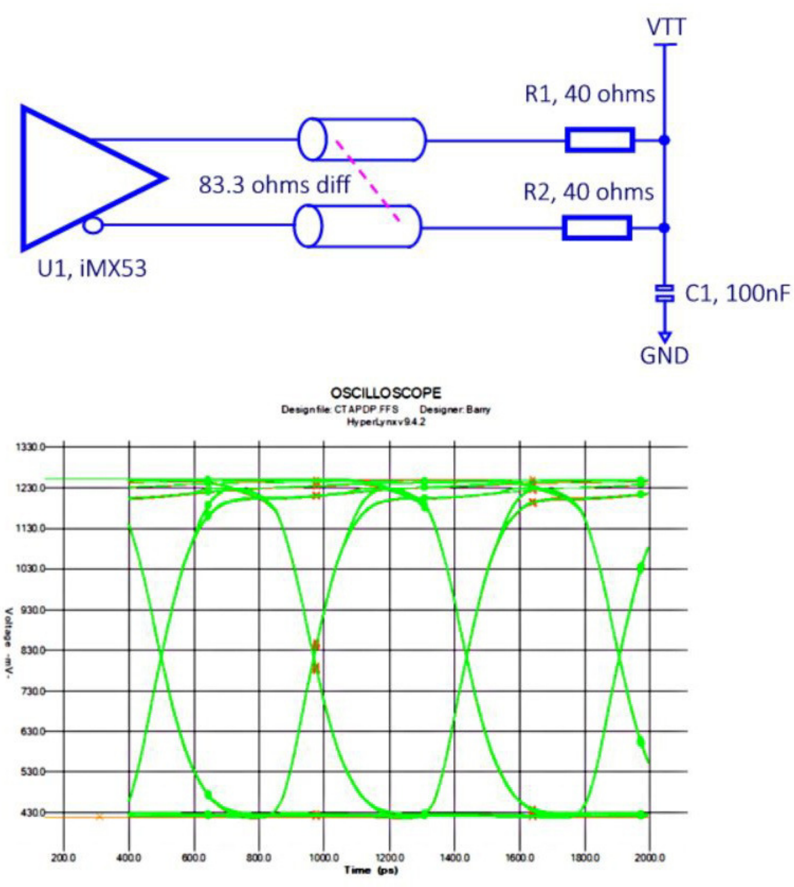


Figure 5(b): Differential center tapped termination.

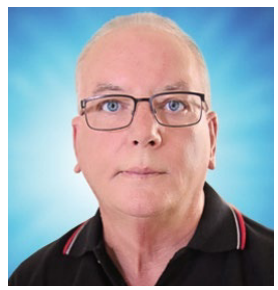
Key Points

- The source impedance of a digital IC driver is typically lower than the impedance of the transmission line. This results in reflections and electromagnetic radiation if not addressed
- Whenever a signal meets an impedance variation, along a transmission line, there will be a reflection which can seriously impact signal integrity
- Impedance discontinuities can also occur due to input gate capacitance, branches, stubs, or test pads; variations in dielectric materials; a neck-down in a via field; skew in a differential pair; or a gap in the return signal path
- Series termination is excellent for point-to-point routes, one load per net. It works well for traces that are electrically short and is used to fanout multiple loads radially from a common source
- Impedance back-matching slows down the rise and fall times and reduces the ringing (over/undershoot) of clock drivers
- Series termination is only used when there is only one receiver/load, and that receiver must be located at the very end of the transmission line
- Subtracting the source impedance from the trace characteristic impedance gives the required series terminator value

- Multi-drop bus topologies require parallel or end termination, which prevents reflections from being formed at the transmission line ends
- The end termination resistor values are twice that of the transmission line as they are in parallel from an AC perspective
- A common method of reducing reflections from differential pairs is to place a resistive load at the end of the pair, which matches the differential impedance of the transmission line
- The single resistor differential termination only terminates the differential mode signal—not the common-mode signal
- Depending on the impedance of the driver, any common-mode signal created will bounce back and forth down the transmission lines
- The differential center tapped termination terminates both differential and common-mode signals. It is best used when you have a low impedance driver on a long transmission line
- If the transmission line is short, reflections still occur but will be overwhelmed by the rising or falling edge of the signal and may not pose a problem **DESIGN007**

Further Reading

- B. Olney, "Impedance Matching–Terminations," *The PCB Design Magazine,* October 2013.
- B. Olney, "DDR3/4 Fly-by Topology Termination and Routing," *Design007 Magazine,* June 2018.
- B. Olney, "Beyond Design: The Fundamental Rules of High-Speed PCB Design, Part 2," *Design007 Magazine,* October 2018.
- E. Bogatin, *Signal and Power Integrity: Simplified,* Prentice Hall, 2008.
- H. W. Johnson & M. Graham, *High-Speed Digital Design: A Handbook of Black Magic,* Prentice Hall, 1993.



Barry Olney is managing director of In-Circuit Design Pty Ltd. (iCD), Australia, a PCB design service bureau that specializes in board-level simulation. The company developed the iCD Design Integrity software incorporating the iCD Stackup, PDN, and CPW Planner. The software can be downloaded at icd.com.au. To read past columns or contact Olney, click here.

Sweat Sensor Detects Stress Levels: May Find Use in Space Exploration

If someone asked you how stressed you are right now, what would you say? A little, a lot, or you don't know?

Those are all valid responses, but they are not especially useful to researchers and medical professionals because they are subjective and not easily quantified. Nonetheless, in lieu of a better method of measuring stress, the common method for years has consisted of a stress questionnaire. The main alternative to the questionnaire, a blood test, can provide quantitative data but requires a trained professional to draw the blood, and the stress of the procedure itself—being poked with a large needle—can skew the results of a lot of people.

But something better might be right around the corner. Wei Gao, assistant professor of medical engineering at Caltech, has produced a wireless sweat sensor that can detect levels of cortisol, a natural compound that is commonly thought of as the body's stress hormone. In a new paper appearing in the journal *Matter,* Gao and his fellow researchers demonstrate how they designed and made the mass-producible device, how it works, how it is effective at detecting cortisol levels in near real-time.

The development of an inexpensive and accurate device for measuring cortisol could allow for more widespread and easier monitoring of stress but also of other conditions including anxiety, post-traumatic stress disorder, and depression—all of which are correlated with changes in cortisol levels.

(Source: Caltech)