

## Rejistor™ Electrically-Adjustable Resistor Technology

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### The Need for Adjustment in Analog Electronics

In the field of analog electronics, the pain of achieving precision is the need for calibration. In general, electronic circuits, systems and solutions, both integrated and discrete, are prone to variations in parameter values of their components. These may be variations in the as-manufactured component values, or may be variations over time or temperature. In any case, these variations may degrade circuit performance, and/or reduce fabrication yield.

As a result, analog electronics relies on a variety of circuit design, calibration and adjustment techniques, to overcome these variations, and achieve the required performance and precision. Typically, circuit calibration is done by adjusting (“trimming”) a resistance element, and the industry relies heavily on a variety of such resistance-trimming techniques. Manual trimpots, laser trimming, digital potentiometers, fusible arrays, and other programmable active devices, are each used in certain circumstances.

However, each of these techniques has one or more limitations. For example, they may have limited frequency range, may have limited precision, may not behave like a resistor unless separate power and ground are present, may be adjustable only once or only in one direction, or may be adjusted only during manufacturing before packaging using expensive equipment. Designers of analog and mixed-signal circuits, with even modest requirements for precision, must always consider how the circuit will be adjusted, and which limitation will be the least painful.

Microbridge’s **Rejistor™** (electronically re-adjustable resistor) is a passive, VLSI- and MEMS-compatible adjustable micro-resistor. It is non-volatile (i.e. doesn’t need power to hold its adjustment), and it is re-adjustable many times, bi-directionally, to very high precision

(e.g. 0.1% to 0.002%, depending on a variety of factors), using only electrical signals. **Rejistors** can also be Temperature Coefficient matched with other **Rejistors**, again using only electrical signals. All adjustments can be carried out at low voltage and low current before and/or after packaging or even in-circuit.

### Rejistor Technology Overview

The **Rejistor** technology is based on standard CMOS chip technology, with post-processing to create suspended micro-structures, as depicted in Figure 1. The microstructures, suspended over a cavity, offer enhanced thermal isolation and low thermal mass, which enables localized, controllable and rapid thermal cycling of electrical resistance elements embedded in the microstructures.

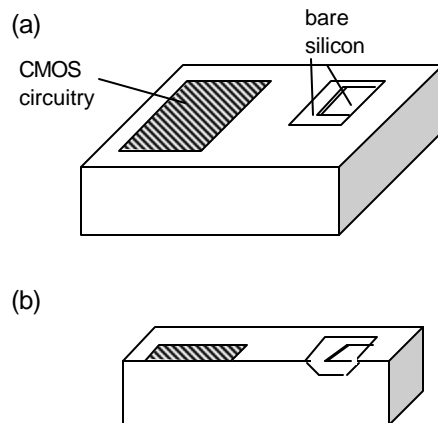


Fig. 1 (a) Typical integrated circuit made by standard CMOS process; (b) after post-process etching (cross-sectional view) to create a cavity and suspended micro-structure. (Schematic drawings not to scale.)

The adjustment of a thermally-isolated functional resistance element is accomplished by locally annealing (heating) the resistance element, gently changing the physical properties of the resistance element with each heat cycle. The algorithms to apply the heat cycles are adaptive, involving a repeating sequence:

- measuring or inferring the functional resistance at room temperature,
- computing pulse parameters for the next temperature cycle,
- applying the high-temperature sequence,
- measuring or inferring the resulting functional resistance at room temperature,
- and so on, until the resulting room-temperature resistance is within the desired tolerance.

This adaptive approach would be impractical without the capability to rapidly heat and cool the microstructure, so that many cycles can be applied in a short time, without requiring high temperature furnace operations, and without affecting other circuitry closely adjacent on the same chip.

### Polysilicon High-Temperature Instability and Adjustability

The *Rejistor* technique is based on the inherent instability of certain materials at high temperatures. In standard CMOS IC technologies, polycrystalline CVD-deposited silicon is one example of such a high-temperature-mutable material. Instability at any temperature is typically seen as a disadvantage, but in this case it is used advantageously to allow high-precision trimming.

For several decades, researchers and patent authors have reported that polysilicon (embedded in typical integrated circuits or in suspended microstructures), became thermally unstable at high temperatures. The prior art has shown that the resistance of polysilicon can be adjusted by passing current through it, or, in general, by heating it to high temperatures. It was also demonstrated that one could decrease resistance (“trim down”) quickly, by using high-temperature pulses, and increase resistance (“trim up”) more slowly by heating at temperatures lower than those required for trimming down. Trimming down could be done quickly over tens of percent of the resistance value, however trimming up

was found to be much slower and consequently more limited in range.

### Thermally-Isolated Microstructures: Practical Bidirectional High-Precision Trimming

While many researchers have noticed high-temperature instability, most of the prior art on intentional thermal trimming has addressed trimming of simple integrated resistors which were not thermally-isolated on microstructures.

Figure 2 shows an example of a pair of polysilicon resistors, (a functional resistor,  $R_1$ , and a heater,  $R_{1h}$ ), designed to be suspended over a rectangular micro-machined cavity.

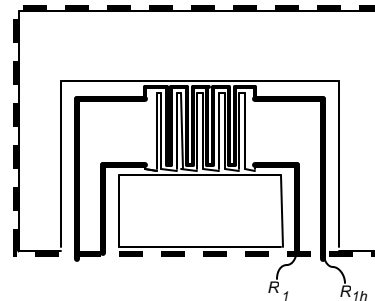


Fig. 2: Top view of a typical layout of a pair of resistors, which may be suspended over a micro-machined cavity having outer edge indicated by the dashed line.

The table below compares electrical tests of two such structures, identical except that one has the micro-machined cavity etched beneath it, while the other does not. The temperature increases were estimated through the known temperature coefficient of resistance of the polysilicon.

	Applied Voltage	Dissipated Power	Temperature Increase	Temperature on chip, 270 $\mu$ m away	Cooling time
Etched	2.5 V	~ 6 mW	~300 °C	~ 0.1 °C	< 0.003 s
Un-etched	10 V	~ 100 mW	~10 °C	~ 2 °C	> 2 s

The un-etched structure needs 10V to apply roughly a tenth of a watt. This achieves only about 10 degrees of temperature rise at the resistor itself, because most of the heat goes

to warming the substrate, as evidenced by the significant temperature rise 270 $\mu$ m away. Of course, the high thermal mass of the substrate prevents rapid cooling.

The etched structure, on the other hand, needed only a quarter of the applied voltage (about one sixteenth of the applied power), to reach 30x greater temperature rise. This was feasible because the thermal isolation was much higher (~50 $^{\circ}$ K/mW vs. less than 1 $^{\circ}$ K/mW for the unetched structure). Accordingly, the rest of the chip experienced negligible temperature rise. Very rapid heating and cooling were evidently attainable, because the thermal mass being heated was far smaller (only the microstructure vs. the entire chip).

Microbridge's techniques rely on this rapid heating and cooling, as a foundation for adaptive algorithms to apply trimming signals. With rapid heating and cooling, one has precise control of heat cycles, as well as the ability to adapt from one cycle to the next. Several cycles can be adaptively applied in a short time period (a few seconds), and one can attain better trimming precision than would otherwise be practical. Microbridge's innovations in microstructure geometry and electrical trimming algorithms allow repeatable, reversible adjustment in a few seconds over a range of tens of percent of the resistance value.

In automated tests of single Microbridge **Rejustors**, individual **Rejustors** have been subjected to repeated trimming operations, both increasing and decreasing, over a range of a few percent to tens of percent, to precision better than 1%, each operation consuming a few seconds or less, for thousands of operations without any significant change in trimming behavior.

### Simple Applications Example: Op Amp Offset and Gain Trimming

Figure 3 shows a simple analog op amp circuit, where trimmable elements are typically used to adjust amplifier gain and offset. When **Rejustors** are tested as shown in this circuit, referred-to-input offsets of a few  $\mu$ V, and gain

control of better than 0.1%, are readily attainable.

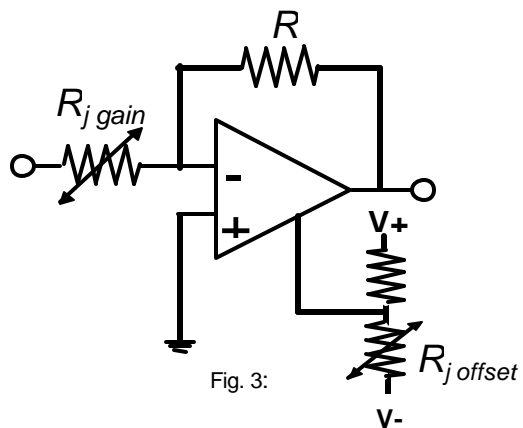


Fig. 3:

### Higher Precision Enhances The Importance of TCR Matching

The ability to do high precision trimming raises the issue of Temperature Coefficient of Resistance (TCR) problems which may not be important at lower precision. The TCR's of electronic components and resistive sensing elements may vary widely (e.g. from zero up to +/- thousands of ppm per  $^{\circ}$ K of temperature change). To understand why this may cause problems in the context of high-precision trimming, one only has to consider the following example. If the TCR of an individual resistor in a circuit were, say, 1000ppm/ $^{\circ}$ K, and if one trims resistance to within a precision of 100ppm, then in order to stay within roughly 100ppm of a trimmed value, one would need to control the operating temperature of the device to within ~0.1 $^{\circ}$ C – not trivial! For mainly this reason, many resistors in many electronics circuits are used as matched pairs, where the TCR's of the resistors are attempted to be matched as well as possible, so that their *relative* TCR (RTCR), is as close to zero as possible.

### eTCR Technique for Adjusting R and RTCR to Independent Values

In the industry at present, the TCR of a material is widely viewed as a given, and never trimmed at the level of an individual device. There has been no practical, cost-

effective means to even measure the TCR of an individual component within an integrated circuit, let alone trim it. Microbridge's **Rejistor** and **eTCR** technology not only electronically adjusts resistance to high precision, but can also measure the RTCR of pairs of **Rejistors** and electronically adjust the TCR to high precision as well. This is an industry first.

Figure 4 shows a sample **eTCR** layout. For example, if  $R_{S1}$  and  $R_{S2}$  are roughly  $\sim 6k\Omega$ , made from standard CMOS gate polysilicon having a TCR of roughly  $\sim 1000 \text{ ppm}/^\circ\text{K}$ , and if  $R_{S2}$  is measured to be exactly  $6000.00\Omega$  with a 6-digit ohmmeter, then  $R_{S1}$  can be trimmed to match the resistance  $R_{S2}$  within 50ppm or better (within  $\sim 0.3\Omega$  of  $6000\Omega$ ). Simultaneously, the TCR of  $R_{S1}$  can be trimmed to match the TCR of  $R_{S2}$  within  $\pm 2 \text{ ppm}/^\circ\text{K}$  or better. Moreover, the relative TCR of  $R_{S1}$  and  $R_{S2}$  can be trimmed deliberately to a non-zero value within a limited range.

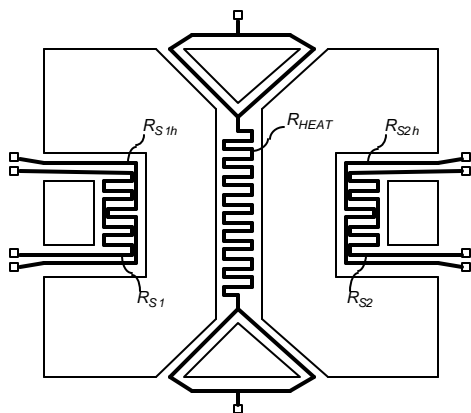


Fig. 4: Top view layout of an **eTCR** circuit, including two **Rejistors** and a heater for measurement of TCR.

### What Can You Do With The **Rejistor**: Wheatstone Bridge Sensor Circuits

Many sensors are used in a Wheatstone Bridge circuit, as shown generically in Figure 5. With no sensor stimulus (e.g. noxious gas or magnetic field) present, and at a constant temperature, the resistive sensing element (labeled 'Sensor'), has a nominal resistance value. The other three resistors in the bridge are designed such that, when the sensor is in

its quiescent state, the mid-points of the two voltage dividers maintain the same voltage, such that the bridge is "balanced". For example, the four resistors, "Sensor",  $R_1$ ,  $R_{jo}$ ,  $R_{jt}$  can be designed to all have the same resistance value, such that the divider midpoints ride at half of the bridge supply voltage. In general, when the sensing element responds to a stimulus, its resistance changes, thereby unbalancing the two bridge mid-points. Fine differences between these two voltages are then amplified, typically with substantial gain. The sensor response may be small, and in principle this type of scheme allows for robust amplification and handling of subtle sensor signals.

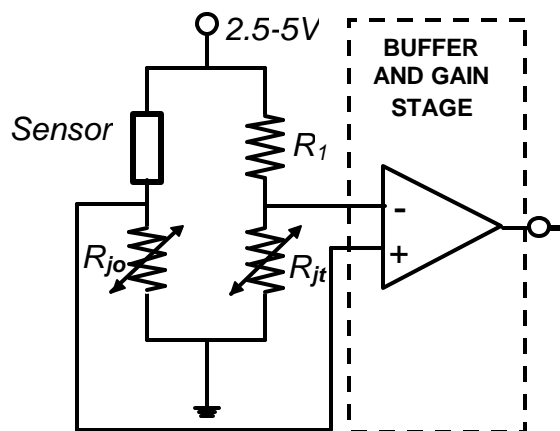


Fig. 5: Typical Wheatstone Bridge circuit with amplification stage.

In practice, however, Wheatstone Bridges are prone to being unbalanced by factors other than the desired sensor response. If, due to minor component variations, the quiescent sensor resistance and its three partner resistances are not related such that the divider mid-points are perfectly matched, then there can be substantial spurious zero-stimulus output. And if the TCR's of the four resistances are not matched, there can be a substantial temperature variation of this quiescent response. Furthermore, the amplification stages are prone to needing offset and gain adjustments.

**Rejistors** with **eTCR** adjustment capability can be readily used in the above configuration.

A pair of RTCR-match-able **Rejustors** can be used as  $R_{jo}$  and  $R_{jt}$ , and another pair can be used to precisely set, and temperature-compensate, the gain of the amplification stage. If needed, further **Rejustors** can be used to regulate the offset of the amplifiers.

### Using the **Rejustor**

There are two principal ways in which **Rejustor** technology may be implemented: as a discrete chip-resistor, or designed into a larger analog or mixed-signal integrated circuit. The modes of use can range from simple adjustment of a discrete component, such as where a manual trim potentiometer may otherwise be used, to the other end of the spectrum, integrated into a system-on-chip (SoC) IC. In between, it may be assembled onto a printed circuit board, module, or thick-film circuit.

Since the adjustment signal sequence is adaptive, a logic processing engine and digital/analog/digital conversion (ADCs and DACs) must be present. The DACs need 8-10-bit resolution, in order to apply the trimming signals, and the quality of the ADCs depends on the trimming precision needed for the application and circuit in question. These elements of the technique may be implemented in a variety of ways:

- Implementation of logic processing:
  - may be simply housed on a nearby PC, connected through the serial port;
  - may be part of the test and measurement system used to test the **Rejustor**, or test/calibrate a system within which the **Rejustor** (discrete or integrated) is functionally embedded;
  - may be part of a larger electronic system within which the **Rejustor** is functionally embedded (e.g. a sensor-based system, electronic equipment, industrial instrumentation, an automobile, etc.);
  - may be on the same chip as the **Rejustor**, as a processor (e.g. 8051, etc.);

- may be on the same chip as the **Rejustor**, as a custom-designed state-machine;
- implementation of digital/analog/digital conversion:
  - may be a separate “trimming instrument” next to the PC on the bench top;
  - may be part of the test and measurement system mentioned above for test/calibration;
  - may be part of the larger electronic system within which the **Rejustor** is functionally embedded;
  - may be on the same chip as the **Rejustor** (whether or not the logic processing is also present on the same chip);

In any case, provided one has access to the required trim pin(s), several ways are available to deliver the trimming signal sequences.

To analyze **Rejustor** usability in a system or on an integrated circuit, the location of four components needs to be considered:

- The **Rejustor** structure itself
- Other analog circuitry needing adjustment
- DAC/ADC
- Algorithm code

The table on the next page analyzes a relevant range of applicable cases.

Optimizing the use and value of **Rejustor** technology comes from understanding the benefits of its numerous features in each application, in a discrete or integrated form.

For example, in some cases the elimination of laser-trimming in the manufacture of an integrated circuit can offer a significant cost reduction. When wafer yield is high, wafer sort may be eliminated, all die could be packaged without exhaustive probing, and “trimming” may be done at final package test. It is only necessary to provide the “trim” input(s), which with clever design may not even require extra physical pin(s) on the device. If further value is

added by allowing subsequent re-trimming “in the system”, then the cost of dedicated pin(s) may be well justified.

In sensor applications electrical calibration may be done after packaging, compensating for both as-manufactured across-wafer variations, and variations due to the stresses typically incurred in assembly processes. This provides not only a cost saving by reducing or eliminating pre-package test/calibration, but also a performance enhancement. The cost of an additional pin, if later re-calibration is

required is often easily justified by the long-term benefits.

In any laser-trimming situation, access to resistors is inescapable. For an active in-circuit trim, where the whole circuit assembly must still permit access to the trim resistors, the cost of handling, complex tooling and probe/connection systems, can far outweigh the simple addition of trim pin(s) for **Rejustor** trimming.

Application	What's on the Chip	What's in the System but not on the chip	What's outside the immediate system
Chip-resistor in DUT board	Just the <b>Rejustor</b> (chip-resistor)	Nothing (it's just a DUT board)	DAC/ADC module Algorithm code
Chip-resistor in signal conditioning module	Just the <b>Rejustor</b> (chip-resistor)	Some signal conditioning circuitry	DAC/ADC module Algorithm code
Trimmable standard analog components	<b>Rejustor</b> , plus simple analog circuitry	--	DAC/ADC module Algorithm code
Embedded in industrial instrumentation	<b>Rejustor</b> , plus simple analog circuitry	DAC/ADC	Algorithm code
Automobile self-calibration	<b>Rejustor</b> , plus simple analog circuitry	DAC/ADC, Algorithm code	--
Integrated semiconductor device or ASIC	<b>Rejustor</b> , Analog circuitry, DAC/ADC	--	Algorithm code
Integrated semiconductor device or ASIC	<b>Rejustor</b> , Analog circuitry, DAC/ADC	Algorithm code	--
Fully Integrated System ( SoC)	<b>Rejustor</b> , Analog circuitry, DAC/ADC, Algorithm code	--	--