menlomicro

The Quest for the Ideal Switch®



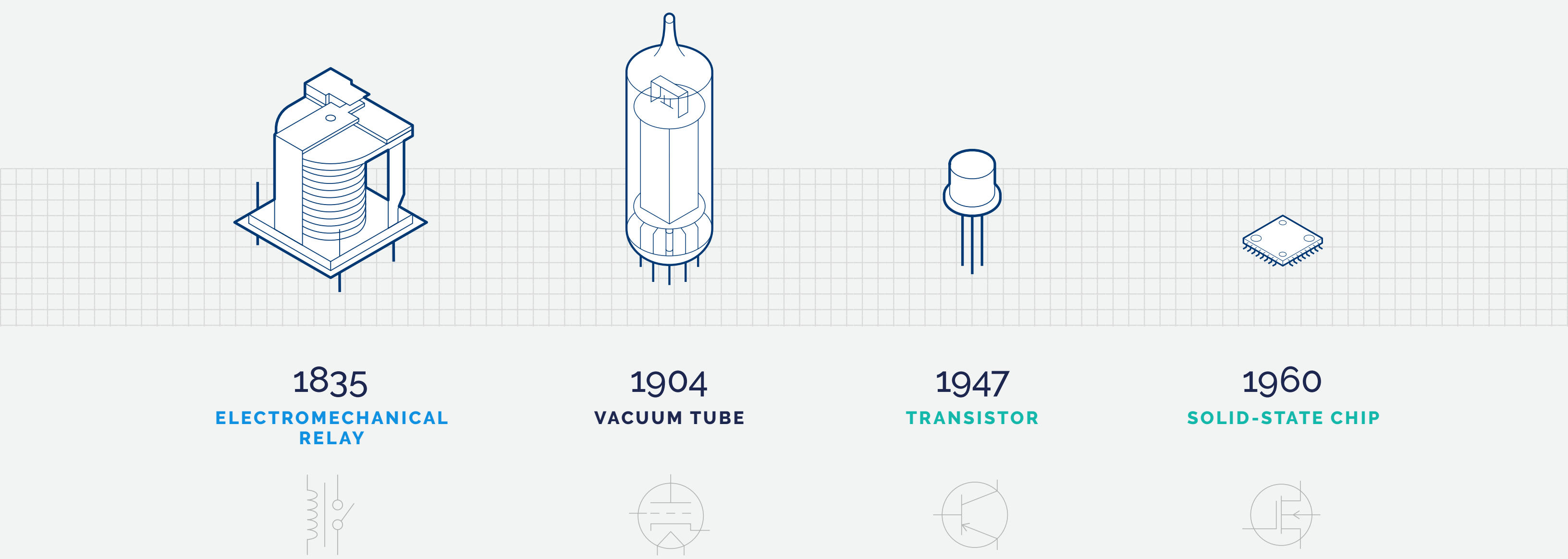

FOR NEARLY TWO CENTURIES, inventors have been working feverishly to create the "ideal" switch. This quest began when William Sturgeon, a shoemaker and dabbler in electricity, created the electromagnet in 1824 which, a decade later, American scientist Joseph Henry used to invent the electromagnetic relay. In 1879 Thomas Edison invented and patented the circuit breaker. Twelve years later, the first "miniature" circuit breaker was invented by Hugo Stotz.

Joseph Henry's electromechanical relay

Today's switching technology and electromechanical relays (EMRs) are rooted in these 19th century inventions which, nonetheless, have made innumerable modern electrical systems possible. Competitors to this technology only appeared in the mid-20th century with the emergence of diodes and today there are numerous types of solid-state or transistor-based switches.

The problem with EMRs however, is that they're big, bulky, slow, and don't last long. On the other hand, solid state switches are inefficient, introducing losses when handling high current or RF signals, and requiring bulky heat sinks. As a result, engineers have to make compromises when choosing between an EMR or a solid-state switch. Engineers have been searching and waiting for a new type of switch that didn't require them to compromise their designs; the perfect switch.

Evolution of switch technology



The perfect switch **in theory:**

When "ON" it's a wire with zero resistance.

When "OFF" it's an open circuit, with infinite resistance.

It doesn't take any power to turn it on and keep it on.

It handles signals from DC to any frequency.

It's small, fast, silent, and lasts forever.

Costs $0 to make.

The latest advances in MEMS switch technology look very much like this perfect switch. So much so, that Menlo Micro has coined their industry-leading switch the "Ideal Switch®".

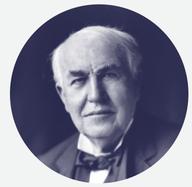
The Ideal Switch **is reality:**

- As low as 0.005Ω (5 Milli-ohms)
- Greater than 10,000,000,000Ω (10 Giga-ohms)
- Less than 0.000000000025 A (25 Pico-amps)
- DC to >60 GHz
- Small, fast, silent and can switch >3B operations
- Built with low-cost, scalable semiconductor process, but is a true metal conductor.

Unlike all other MEMS switches, the Ideal Switch® is a universal micro-mechanical switch because it can switch both AC/DC and RF power. It is based on a proprietary manufacturing process and materials science originally developed at General Electric (GE) that is now being further developed and commercialized by Menlo Microsystems (Menlo Micro). Menlo Micro was established in 2016 and is backed by Microsemi, Corning, Paladin Capital Group, Future Shape, Standard Investments, and Piva. The Ideal Switch® is the result of over 15 years of effort and hundreds of millions of dollars invested.

To understand the benefits of MEMS switches and Menlo Micro's Ideal Switch® technology in particular, it is important to understand both within the context of their predecessors.

Menlo Micro origins

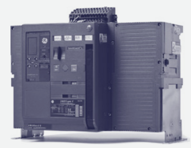


1879

Edison patents the circuit breaker.

1892

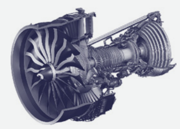
General Electric is formed, combining Edison's various companies.



Over 100 years of experience in high voltage, high reliability industrial controls.

2004

GE starts effort to reinvent the circuit breaker with a MEMS switch.



GE develops core IP, including high temperature, high reliability metal alloy science.

2016

Menlo Micro is formed to commercialize the Ideal Switch®.

Switches are everywhere.

It is safe to assume that there are trillions of electrical switches in use throughout the world—and that doesn't even include the number of transistors on a single microprocessor, which can reach to the billions.

There are hundreds of switches in an average home, the same in a passenger car, tens of thousands in a Boeing 747, and hundreds of thousands in the factory that built those switches. In short, switches are everywhere and serve an enormous number of applications, from simple, manual light switches to huge relays that manage the flow of electricity within the power grid.

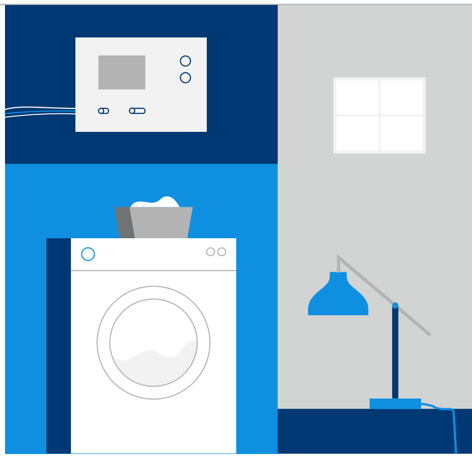
Switches are an essential ingredient in almost every electronic system on the planet, from cars to medical instruments, to smart appliances, to cell towers, to the latest smartphones, and everything in between.

All these switches serve two basic functions: connecting and disconnecting ("switching") some source of electricity or data ("signals") to/from a device or subsystem and routing it from one place to another. The most obvious of these signals are AC or DC power, audio (very low-frequency energy), and electromagnetic energy (e.g., radio frequency waves). Here's where things get interesting.

Each of these signals has entirely different characteristics that require specific technologies to switch it, and it is necessary to see how they differ.

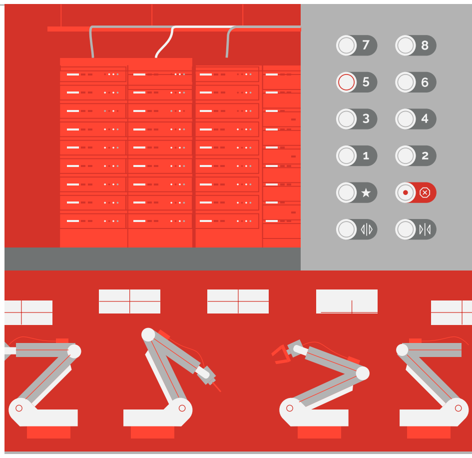
In our homes.

- Managing our heat, AC, & lights.
- Our appliances are loaded with them.
- Circuit breakers that keep it all safe.



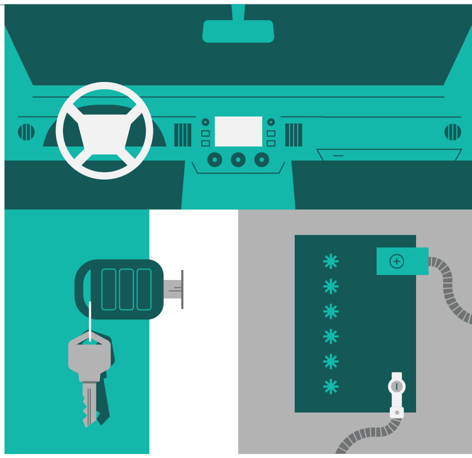
At work.

- Control the elevators, lighting, HVAC.
- All our computers, servers, comms.
- Manage factories and all equipment inside them.



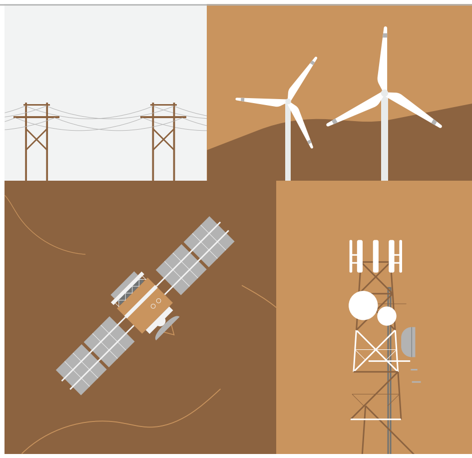
In our cars.

- Unlock the doors and start the engine.
- Turn on and tune the radio.
- Control the wipers, windows.
- Manage the battery.



The world at large.

- Switches control the electricity flowing from power plants to the grid to our homes.
- Switches control the data zipping around the world to our computers and smartphones.



The switch technology landscape.

TYPE	APPLICATION
Electromechanical (Reed and EMR)	Electrical power, RF and microwave power
Silicon transistors (MOSFET and IGBT)	Electrical power
Gallium arsenide transistors (GaAs)	RF and microwave power
Gallium nitride transistors (GaN)	Electrical power, RF, and microwave power
PIN diodes	RF and microwave power
RF MEMS	RF and microwave tuning and switching
"Universal" MEMS switch (Menlo Micro's Ideal Switch® technology)	RF and microwave tuning and switching, AC/DC power switching

Electromechanical Relays

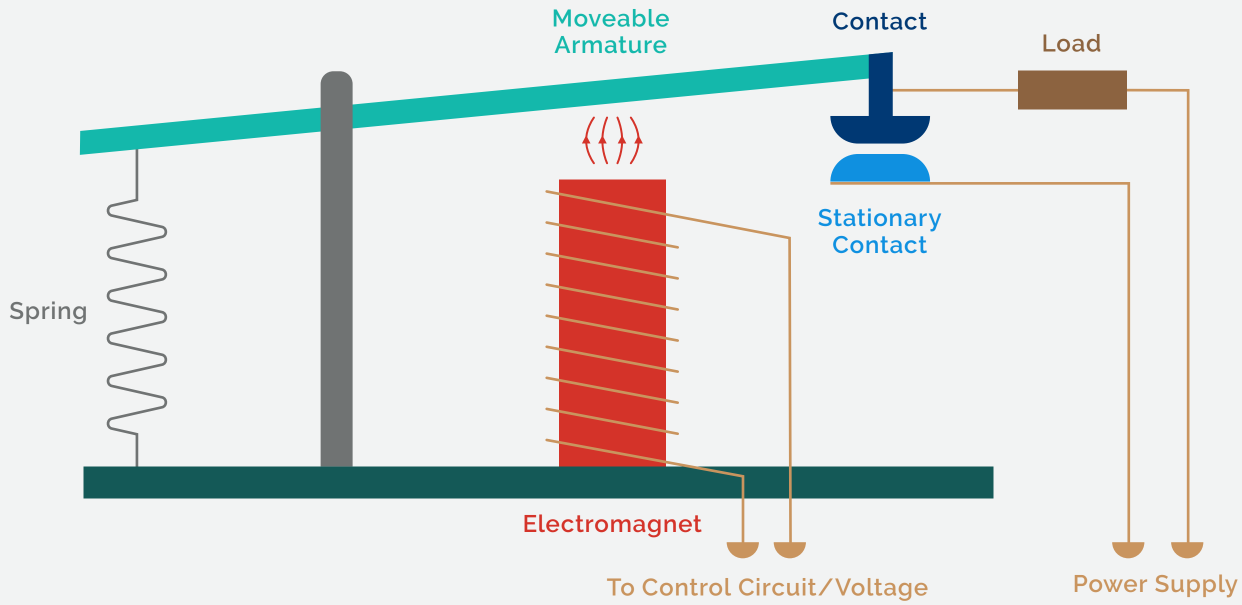
There are hundreds of different electromechanical relays and they are used in thousands of applications in which they switch electrical or RF and microwave power. An electromechanical relay consists of a movable armature, a movable contact and a fixed one, a spring, and an electromagnet formed as a coil just as they did when they were originally invented in the 19th century.

When there is no voltage present at the coil terminals, the relay contacts are open, so the circuit is "off." A voltage applied to the coils of the electromagnet generates an electric field that draws the movable contact to the fixed one, closing the circuit. When this voltage is removed, a spring pulls the contact up to its original position, switching the circuit "off."

The typical electromechanical switch, unchanged since the 19th century!

This diagram shows the electromagnet with a surrounding coil, movable armature with contact at the end and the stationary contact, mounted on the circuit board.

In the image below, the spring on the left maintains the armature in its resting position when there isn't any voltage applied to the coils.



Solid-state Switches

Metal Oxide Semiconductor Field-effect Transistor (MOSFET)

The venerable MOSFET was invented in 1959 and serves many purposes. MOSFETs are found in applications ranging from audio amplification to the power MOSFET, whose fast-switching speed makes it suitable for switching in power supplies at high voltages and currents. The power MOSFET is one of the most widely used devices in power supplies, DC-DC converters, and motor controllers.

Insulated-gate Bipolar Transistors (IGBT)

Like MOSFETs, IGBTs (circa 1984) are useful for fast switching of high electric voltages and current with high efficiency. They essentially combine the high-current-handling ability of a bipolar transistor with the controllability of a MOSFET. An IGBT can handle voltages greater than 1 kV and currents greater than 500 A, which has made them the "go-to" technology for switched-mode power supplies, traction motor control and induction heating. However, their switching frequency is lower than that of a power MOSFET; they cannot block high reverse voltages, and they have no application in switching at RF and microwave frequencies.

Gallium Arsenide (GaAs) Switches

Gallium arsenide (circa 1975) is one of the most versatile compound semiconductor materials, as it is used in everything from solar cells to laser and infrared light-emitting diodes, and RF, microwave, and millimeter-wave low-noise amplifiers, power amplifiers, and switches. GaAs switches generally operate to mmWave frequencies with low power levels (under 1 W).

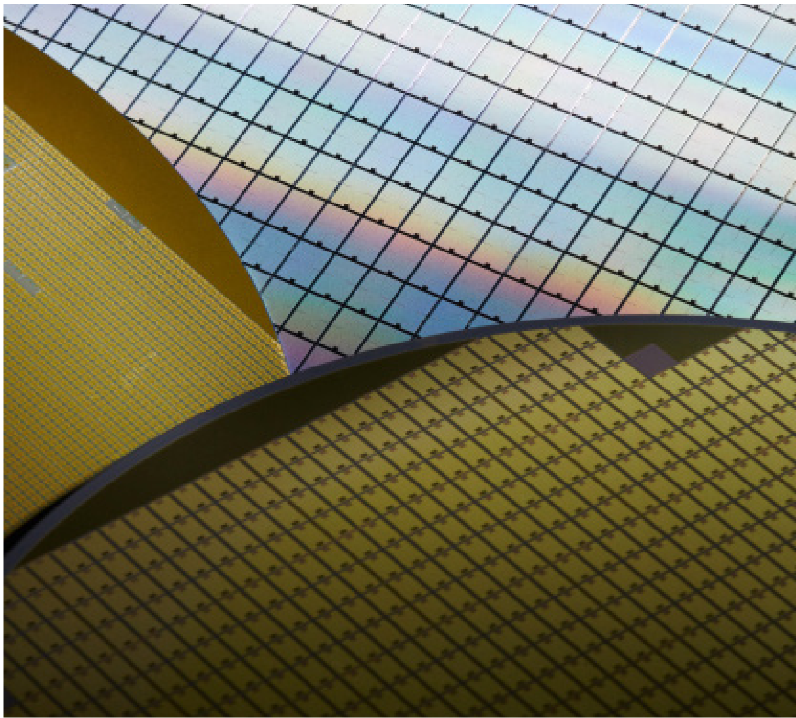
Gallium Nitride (GaN) Switches

GaN (circa 1990) is the most recent technology to be used for RF-switching applications, for which it is just now being commercialized. It has also been making inroads into the power supply market as it can operate at high voltages with very high switching speeds, and its power density is the highest for any semiconductor material. GaN switches currently operate over broad bandwidths, handle about 100 W, and switch in less than 50 ns.

PIN Diodes

The PIN diode (circa 1950) is a workhorse in the RF and microwave industry as, along with switches, it can be used in limiters, phase shifters, modulators, and attenuators. PIN diode switches can operate up to about 50 GHz, and one of their most important features in switching applications is their ability to control relatively high-power RF signals. However, PIN diodes cannot be used at lower frequencies because in this region they function as rectifiers.

Various semiconductor/CMOS wafers.



MEMS technology is enhancing lives everywhere. They capture sounds, measure pressure and movement, and improve vehicle safety.

MEMS Technology

MEMS technology and its applications have taken quite a long time to develop. Even though the microsystem concept began to take hold in the 1970s, it took nearly another quarter-century for the first commercial MEMS product to be introduced. This was Analog Devices' ADXL50 accelerometer, which established the company as the pioneer in turning what had been a promising idea into a commercial product.

MEMS sensors and actuators are now widely available from hundreds of vendors, and MEMS accelerometers, for example, have been the universal choice for use in airbag deployment circuits by the automotive industry since the mid-1990s. Digital micromirror devices (so named for their ability to be digitally controlled) have also been used for years to form optical images on projector lenses on movie theatre screens. MEMS-based Inertial Measurement Units are also in widespread use for navigation systems, and other MEMS applications include miniaturized microphones, speakers, energy harvesters for environmental sources, sensors for measuring pressure, gas, and temperature, and several types of strain gauges.

Conspicuous in its absence from this list is the switch, for which MEMS technology is logically an ideal application, as a switch has movable parts (a fundamental feature of MEMS in general). However, a microelectromechanical switch is different than any other type of MEMS device, so much different that developing and commercializing a reliable MEMS switch product has eluded researchers for the past 40+ years. These efforts consumed the resources of many companies, causing nearly all of them to exit the field before they could achieve commercial success. In addition, almost all these efforts were focused on purely RF applications, to the point where MEMS switches had become synonymous with RF MEMS.

Today, only a few companies remain in the field of MEMS switches, principally Analog Devices, Cavendish Kinetics (now Qorvo), who are both focused on RF applications, and Menlo Micro. All three companies have developed their own specific, often proprietary, techniques that have taken many years of effort and funding to realize. Prior to Analog Devices, Cavendish Kinetics, and Menlo Micro, there were dozens of development efforts, dating back to the 1980s, to bring a reliable and cost-effective MEMS switch to market. The reasons why these efforts came up short are numerous, such as limited resources, a lack of fabrication facilities and control of the fabrication process, and most importantly, the inability to find the right materials to solve the unique challenges required to fabricate MEMS switches with the reliability, manufacturability, performance, and the low-cost requirements of a commercial product.

There are good reasons why so much effort and resources were expended on MEMS switch development. A MEMS switch can potentially replace electromechanical and semiconductor switches in their core applications, especially in test and measurement and RF and microwave systems. They are smaller and lighter, consume very little power, switch at high speeds, have almost no insertion loss and very high isolation, can potentially operate well into the millimeter-wave region, and generate little intermodulation distortion—all delivered within the confines of a tiny package.

MEMS contact switches

There are a variety of MEMS switch variants, of which ohmic and capacitive types predominate. Menlo Micro (along with Analog Devices) take an ohmic approach (of or relating to a circuit element), while Cavendish Kinetics switches are capacitive.

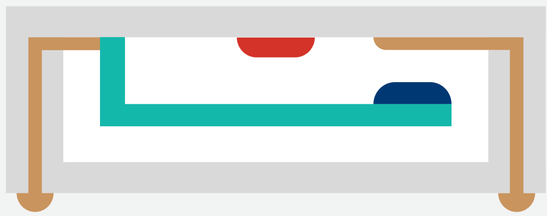
In the case of an ohmic MEMS switch, such as those manufactured by Menlo Micro, they operate in the following fashion: when a DC voltage, applied to the gate electrode of the switch, reaches a specific value, the beam (or cantilever) bends downward due to electrostatic force and meets the contact below it—connecting the input to the output.

When the DC voltage falls below this value, the beam returns to its original position. All this occurs in microseconds.

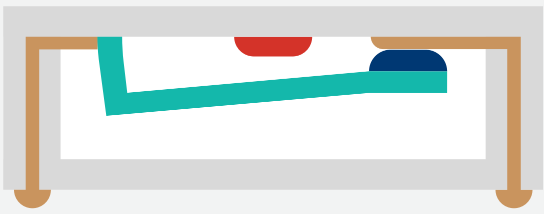
If an electromechanical relay comes to mind, it's because both an ohmic MEMS switch and an electromechanical relay function in the same way: a moving part and a fixed contact make and break a circuit. The difference, of course, is that a MEMS switch is microscopic in size, is created on a wafer in a semiconductor fab and has virtually no mass.

The key challenge is how to manufacture these tiny devices at scale and be able to configure them to withstand thousands of volts, tens of amps, and kilowatts of RF power—and do so for years, or even decades, without failure.

Example of a MEMS switch from Menlo Micro



The beam is in its resting position, as no voltage has been applied to the gate electrode.



Once voltage has been applied, the beam bends, connecting the RF input with the RF output.

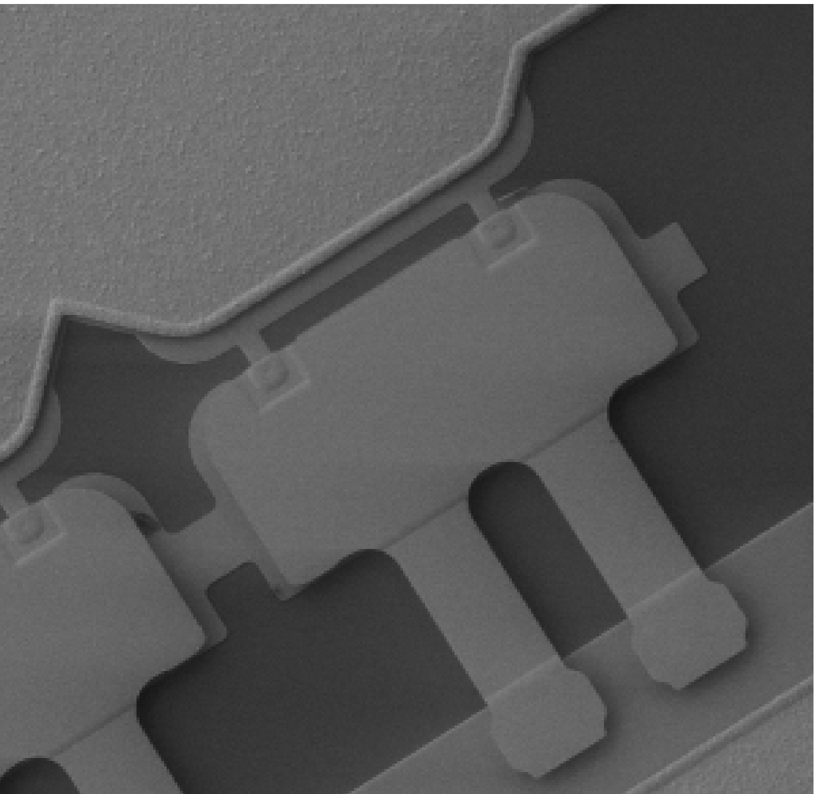
The Evolution of a Micro-Mechanical Universal Switch at Menlo Micro

While Analog Devices and Cavendish have developed commercially available RF MEMS switches, no one has been able to develop MEMS technology that would allow the switch to be used for both RF and high-power applications. The holy grail has always been a universal MEMS switch, able to handle RF up to GHz and AC/DC power up to kV. Menlo Micro's Ideal Switch® is proving to be that universal MEMS switch.

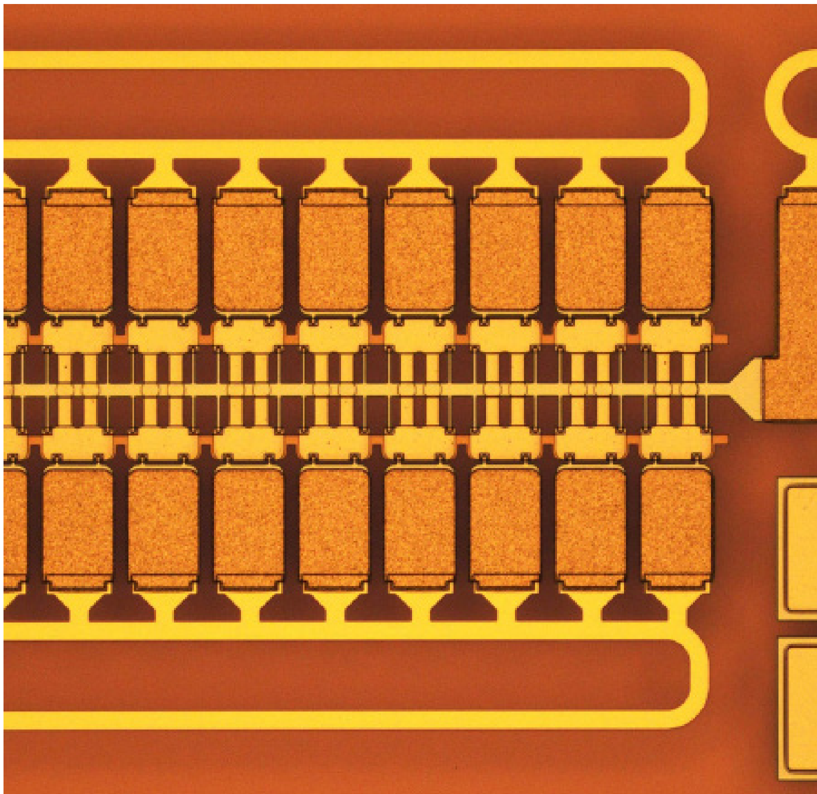
The Ideal Switch® technology now being commercialized by Menlo Micro has roots within GE, which at first might seem like an unlikely source. However, GE's R&D resources span a range of disciplines rarely found in a single company, from chemical engineering to metallurgy, semiconductor electronics and packaging, and most critically, decades of experience in high-temperature alloys, failure analysis, and reliability modeling. All are required to solve problems and develop solutions for GE's demanding industrial businesses, from aircraft and their turbine engines to electrical power generation, trains, oil and gas exploration, mining, hydropower, wind turbines, and magnetic resonance imaging (MRI) equipment.

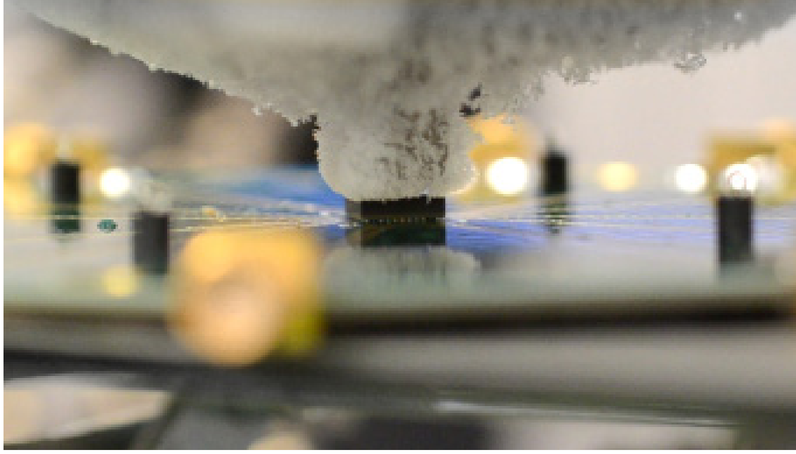
Expertise across all of GE's R&D disciplines was required to solve some of the fundamental reliability challenges for universal MEMS contact switches and, along the way, develop a manufacturing platform that could create universal MEMS switches capable of handling kilowatts of power over long operating lifetimes. The result is a proprietary process that applies semiconductor manufacturing techniques to the production of micro electro-mechanical switches.

A microscope image of Menlo Micro's Ideal Switch® "unit cell" (one individual MEMS contact)



A microscope image of one of many possible cell arrays possible with Menlo Micro's Ideal Switch®.





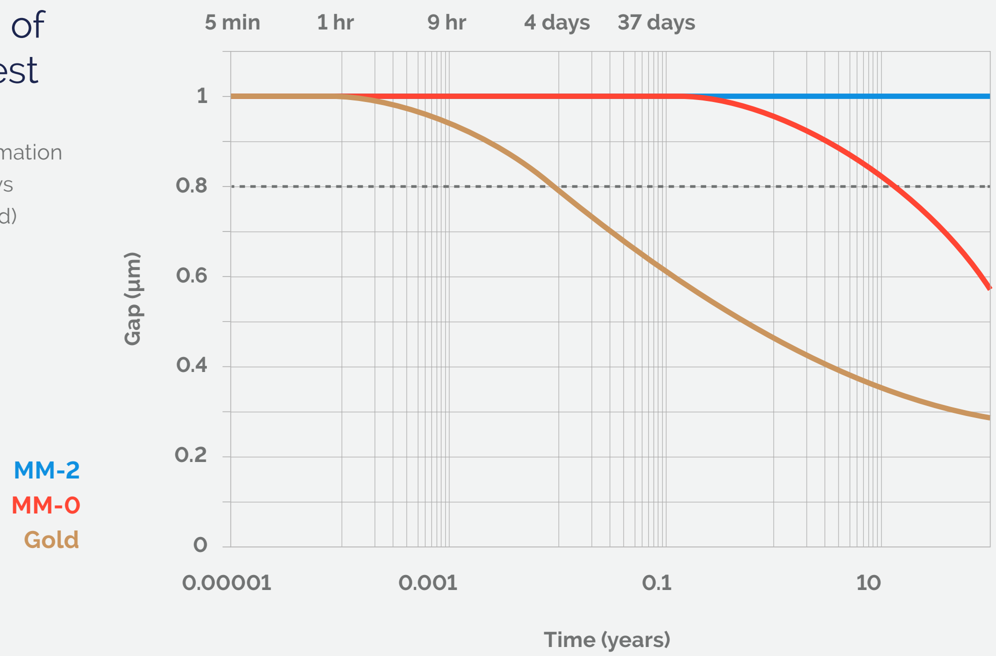
Menlo devices must work in both hot and cold conditions. Shown here is a test at -40° C.

The impetus for universal MEMS switch development at GE in 2004 was the company's desire to find an alternative to traditional mechanical relays for remotely-programmable, very-high-power circuit breakers. The ideal solution would handle high power at the speed of solid-state technology with the ability to perform reliably for decades of life, but without the losses associated with solid-state devices. Existing ohmic MEMS switches from multiple vendors were considered—but, at the time, a lack of reliability under harsh environmental conditions ruled them all out. None of the other technologies checked all the boxes either, so GE decided to embark on an effort to create their own ohmic MEMS switches from scratch.

Ohmic MEMS switches have two primary failure mechanisms: metal fatigue and contact wear. GE researchers determined that while metals are excellent conductors, they are not good spring materials for a cantilever because they deform over time especially with variations in temperature. So, GE began an exhaustive process of materials evaluation that led to a proprietary fabrication process and a proprietary electrodeposited alloy. The result was a cantilever that combined mechanical properties near those of silicon with the conductivity of a metal. These alloys are the key components used by Menlo Micro to fabricate MEMS ohmic switches that can handle kilowatts of power (and therefore high-temperature operation) over decades of useful life.

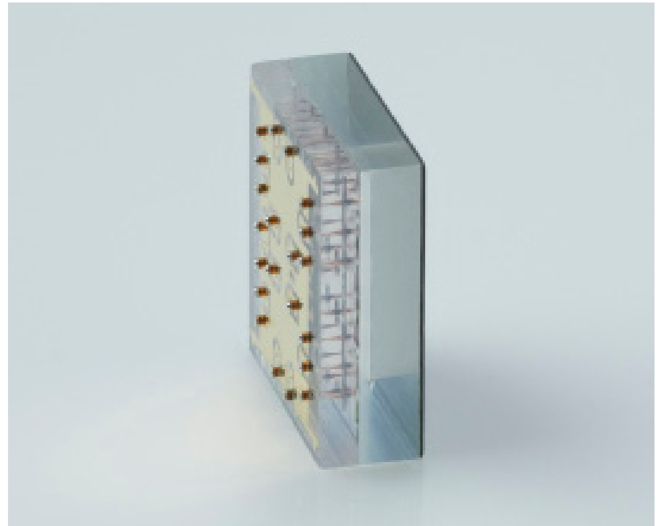
Menlo Micro models of an accelerated life test

The chart here shows switch deformation built with various Menlo Micro alloys when compared to pure metal (gold) MEMS switches.

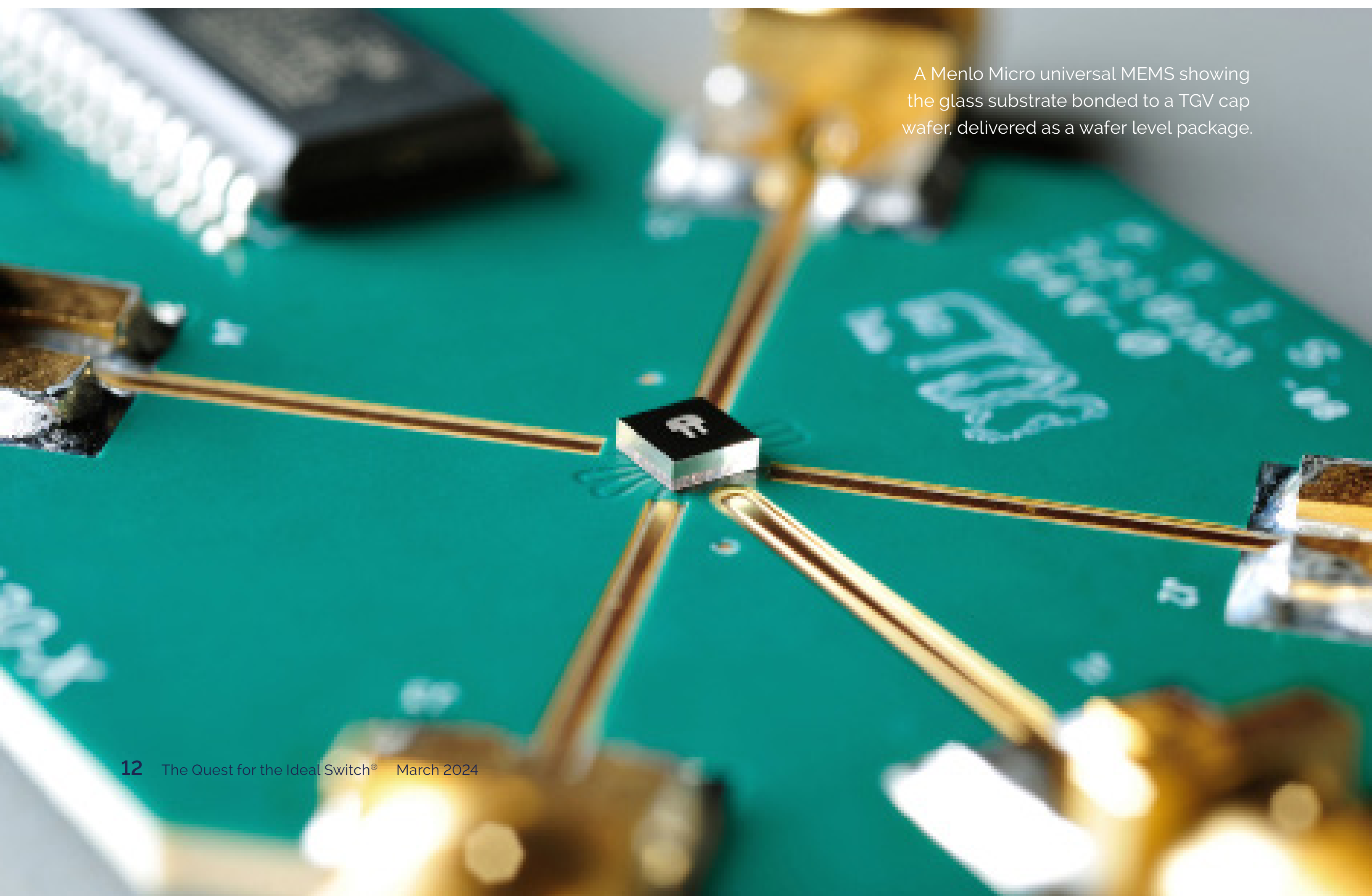


The final key attribute to making a reliable universal MEMS switch is the packaging. Maintaining a stable environment for the switch to operate in, while employing a packaging process capable of scaling for low-cost manufacturing, is critical to creating a commercially viable universal MEMS switch. Working with Corning, Menlo Micro demonstrated the integration of an innovative through glass via (TGV) packaging technology for universal MEMS switches, which allows Menlo Micro's Ideal Switch® to be housed in extremely small chip-scale packages.

As a result, Menlo Micro has reduced the size of its products by more than 60% when compared with wire-bond packages. This allows increased channel density while reducing size, weight, power, and cost. For RF and microwave applications, eliminating wire bonds and replacing them with short, well-controlled TGVs, has reduced package parasitics by more than 75%, which allows the technology to operate over a wide range of frequencies from DC to beyond 50 GHz.



The profile view of a Menlo Micro product, highlighting the through-glass-vias.



A Menlo Micro universal MEMS showing the glass substrate bonded to a TGV cap wafer, delivered as a wafer level package.

Advantages of Menlo Micro's Ideal Switch® Technology

Menlo Micro's Ideal Switch® has several core attributes that define its overall advantages:

The ability to switch AC/DC power, as well as signals, from very low to very high frequencies

Other MEMS switch technologies have been designed to switch RF signals but only Menlo Micro's Ideal Switch® can also handle AC and DC power. This opens up more potential markets and applications than previous MEMS switch companies addressed.

Small size, light weight

Traditional switching technology, like mechanical relays, can be large and heavy, taking up valuable space on circuit boards. Menlo Micro's switching elements are smaller than the width of a human hair, 50 microns by 50 microns, and can handle electric currents of over 400 amperes. The Ideal Switch® also eliminates the space taken up by heatsinks that many traditional switching technologies require. This allows many more switches to be accommodated in a given area.

No external components

In contrast to other technologies, Menlo Micro switches require few if any external discrete components. In addition to reducing the bill of materials, this lowers cost and design complexity and increases switch density. In some cases, their combined small size and reduced component count allows Menlo's Ideal Switch® to be used in smaller form factor systems.

Low power consumption

Menlo Micro's Ideal Switch® consumes a tiny fraction of power, which benefits every application, from improving phone battery life, wireless-enabled IoT devices and large switch matrices. This improves the efficiency of entire systems.

Long operating lifetime

The Ideal Switch® can survive over 3 billion cycles without degrading performance. With lifetimes 1000x longer than a mechanical relay, the Ideal Switch® is one of the most reliable switches available on the market. Menlo has a roadmap to release even longer lifetime switches in the very near future, exceeding 25 to 50 billion operations. This makes them well suited not only for replacing electromechanical devices, but in certain applications, for replacing solid-state switches as well.

High-density glass packaging

Menlo Micro's Ideal Switch® process has been integrated with high-performance glass substrates, which allows its switch products to exploit the benefits of the substrate's high isolation and superior RF performance.

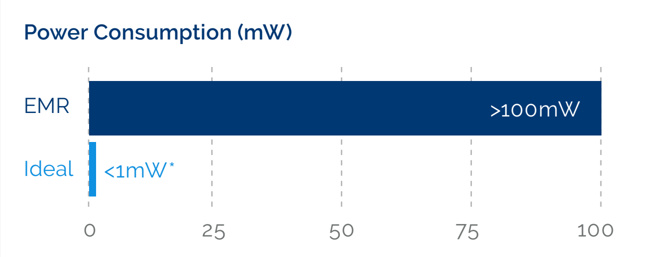
Fast switching speed

While a typical switch may operate in a few milliseconds (10e-3), the Ideal Switch® can operate 1000x faster, in only a few microseconds (10e-6). Although some solid-state switches are still faster, as low as a few nanoseconds (10e-9), for the bulk of switching applications, microsecond-level speed is more than sufficient.

The Ideal Switch® compared to electromechanical relays

100X LESS POWER

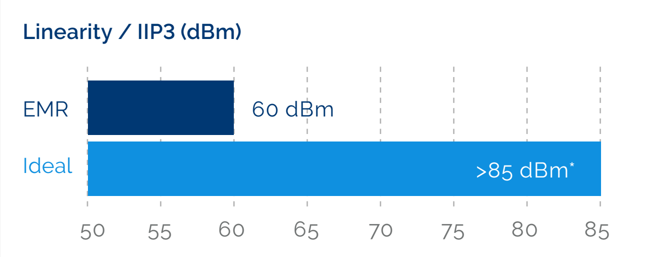
Longer battery life, less heat, new form factors



*Power needed to actuate a single switch

100X HIGHER LINEARITY

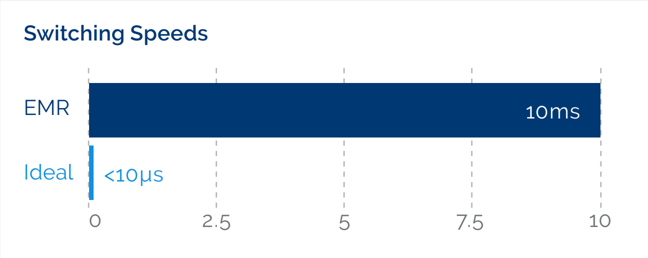
Distortion-free RF signal



*Menlo RF switch compared to typical RF coax switch performance.

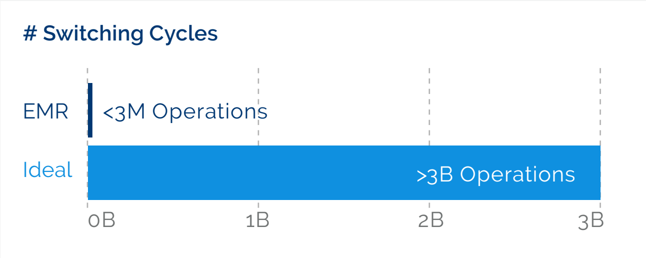
SWITCHES 1000X FASTER

New capabilities, new applications



1000X LONGER LIFE

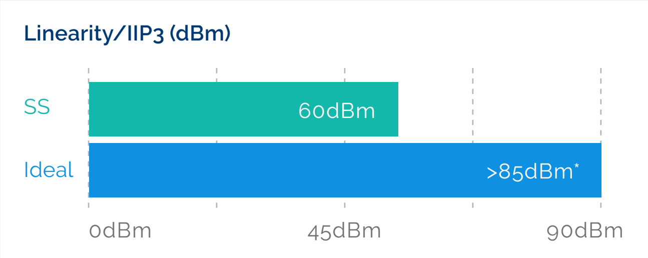
Massive reliability gain



The Ideal Switch® compared to solid-state switches

100X MAGNITUDE BETTER LINEARITY

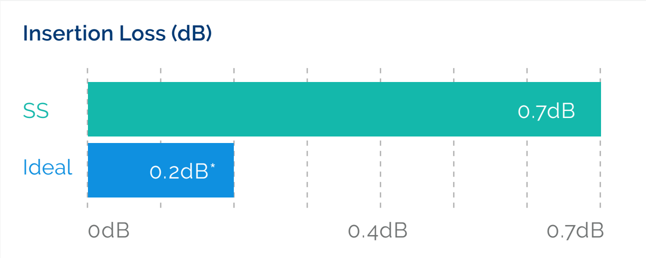
More bandwidth, higher data-rates



*Menlo RF switch compared to typical GaN & PIN diode switch performance.

>0.5dB LOWER LOSS

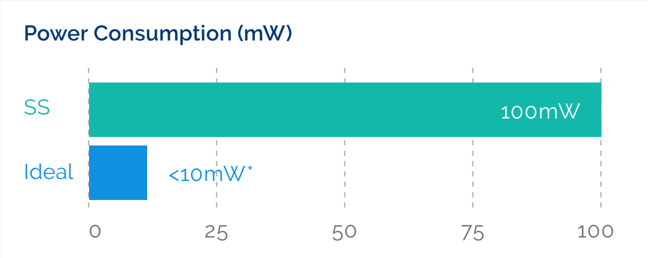
Longer battery life, no big, heavy heatsinks



*Menlo RF switch compared to typical GaN & PIN diode switch performance.

10X LESS POWER

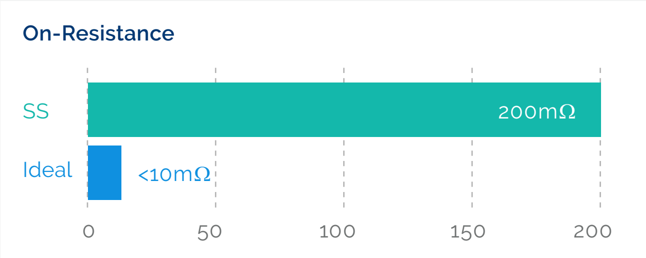
Longer battery life, less heat, new form factors



*Power needed to actuate a single "smart" switch

85% LESS RESISTANCE = NO HEATSINKS

No heatsinks = massive weight, size and cost savings



*Typical Menlo Ron for >200 contacts compared to typical SSR.

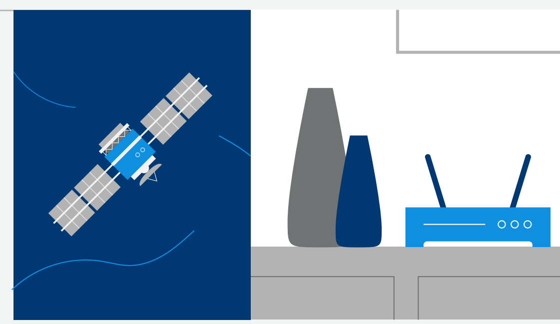
Applications for Menlo's Ideal Switch®

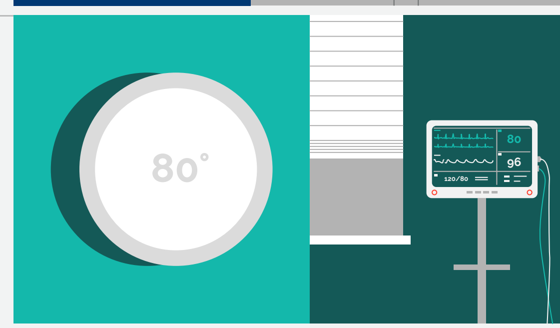
The world of applications for the Ideal Switch® is far reaching/expansive across industries. Menlo Micro has attempted to categorize the various types of end applications into three key segments or categories: (1) RF & microwave switching (2) low frequency/general purpose switching and (3) AC/DC power switching.

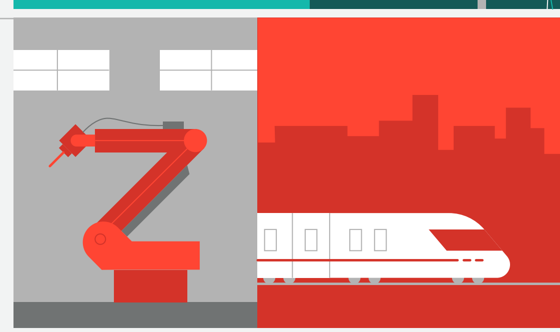
In each of these categories, Menlo Micro has identified applications in multiple end markets, where its Ideal Switch® technology can bring a 99%+ reduction in key metrics including size, weight, power, and cost (SWAP-C). These reductions enable hardware manufacturers and designers to come up with completely new designs.

Everything will be smaller, waste less electricity, and be more cost-effective.

	APPLICATIONS	NEEDS
RF/Microwave Switching	• 5G Cell networks • Radio • Radar • Satellite • WiFi/Connectivity	• Reliability • Low distortion • Low signal losses • Power efficiency
General Purpose Switching	• Telecom • Test & Measurement • Medical • Automotive • Consumer	• Reliability • Fast switching • Frequent switching • Power efficiency • Small, light, cost-effective
Smart AC/DC Power Switching	• Industrial IoT • Home automation • Battery management • Transportation • Motor control	• Low losses, no heat • Speed and reliability • Power efficiency • Lightweight • Smart controls







RF & Microwave Switching

The unique materials used in Menlo Micro's Ideal Switch® technology is especially well-suited for RF and microwave subsystems, which are key to next-generation 5G systems. Menlo Micro's switches are made from metals and metal alloys that are deposited onto a fully isolating glass substrate enclosed in a hermetic air cavity. This provides the best possible environment for routing and switching high-frequency signals. Some examples of RF applications include:

Tunable and multiplexed filters

Filters are employed in RF and microwave systems to reduce interference by rejecting unwanted signals. With the proliferation of frequency bands, having flexible radio architectures that can switch to different bands "on demand" becomes critical. Menlo Micro RF switches are perfect for these applications because they have ultra-low losses and introduce practically zero distortion (non-linearity) into the circuit. They also provide orders of magnitude lower distortion than solid-state switches and orders of magnitude longer lifetime than RF mechanical relays. These performance improvements can help to reduce the thermal footprint of the system and decrease the number of components and the overall size (volume), by more than 90%.

MM6005:
High-power miniaturized reconfigurable filter, a 90% reduction over solid-state designs.

Antenna tuning/switching/beamforming and radar

Systems that cover a broad frequency range often use multiple antennas, each one suited to a specific frequency range. Menlo Micro's RF switches are an excellent alternative to traditional switches for selecting or tuning various antennas. The ability to handle very high voltages (hundreds of volts) make the switches suitable for antennas where such high voltages can be present. The very broadband nature of Menlo Micro's architecture allows for designs that can operate well into the millimeter-wave region (greater than 60 GHz), which is a key trend for advanced 5G communications. In addition, their low-loss and high-linearity allow the creation of high-power phase shifters and other tuning elements that can replace unreliable mechanical devices for applications such as electronically steerable, or active beam-steering antennas. The same concepts can be applied to Active Electronically Scanned Array (AESA) radar systems that are replacing legacy design techniques used in electronic warfare (EW) systems as well. Menlo Micro's ability to develop massive arrays of miniature high-power switches can create much higher performance radar arrays than what can be achieved with traditional solid- state technology.

High-Frequency Switch Matrices

Many test and measurement systems need to switch hundreds or even thousands of RF signal paths when testing different products with multiple instruments. This can become a very complicated problem because the density of RF switching and the performance required creates massive RF switch matrices that require racks of equipment. Menlo Micro's RF switches are well suited for these use cases because they combine high RF performance with low power consumption, minimal distortion, and most importantly a substantially smaller footprint. When compared to an electromechanical relay used in such applications, the volume occupied by a single Menlo Micro switch would be just 25 mm^3 while a relay would consume up to 30,000 mm^3. When arrays of switches are required to accommodate 128 x 128 or 256 x 256 signals, the size of the system will grow very quickly. In addition, operating lifetime is more than 3 billion operations versus 10 million operations for the typical RF relay, and the switching speed is less than 5µs versus 5ms.

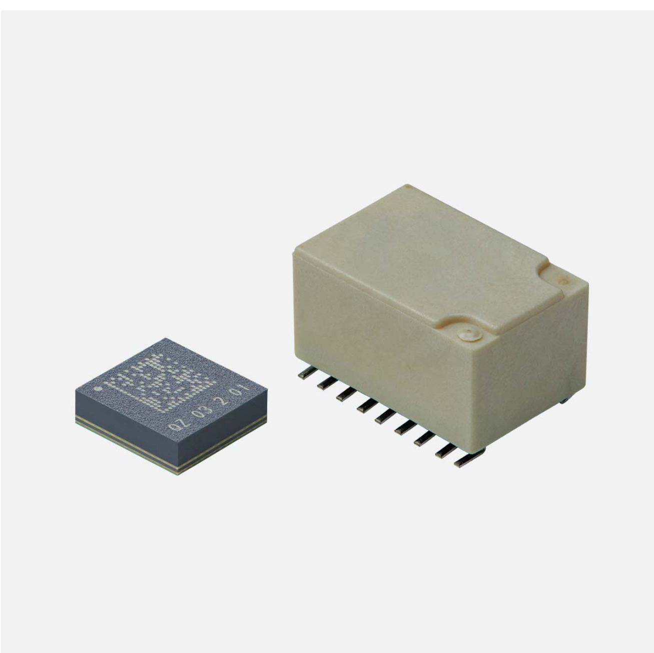
Low-Frequency/ General Purpose Switching

Densely-Populated Switch Matrices

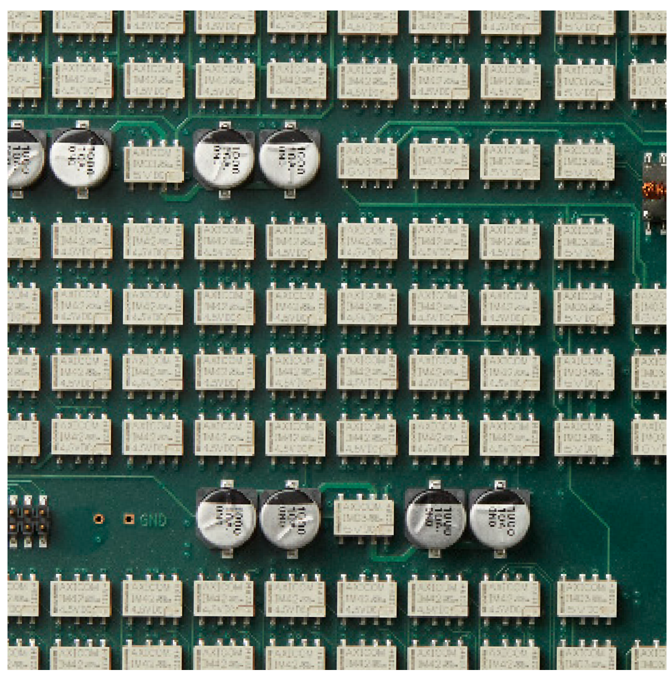
Telecommunications systems, medical equipment, and various test and measurement systems require switching of dozens or even hundreds of signal paths. These can be either DC or low-frequency AC signals, with relatively high voltages (up to 1000V) and a few amps of current. Electromechanical or reed relays have been the switch of choice for decades because high-density solid-state solutions cannot handle high power while meeting low-leakage and high-isolation requirements. However, Menlo Micro switches can not only meet these requirements, but do so in a fraction of the footprint with minimal power consumption.

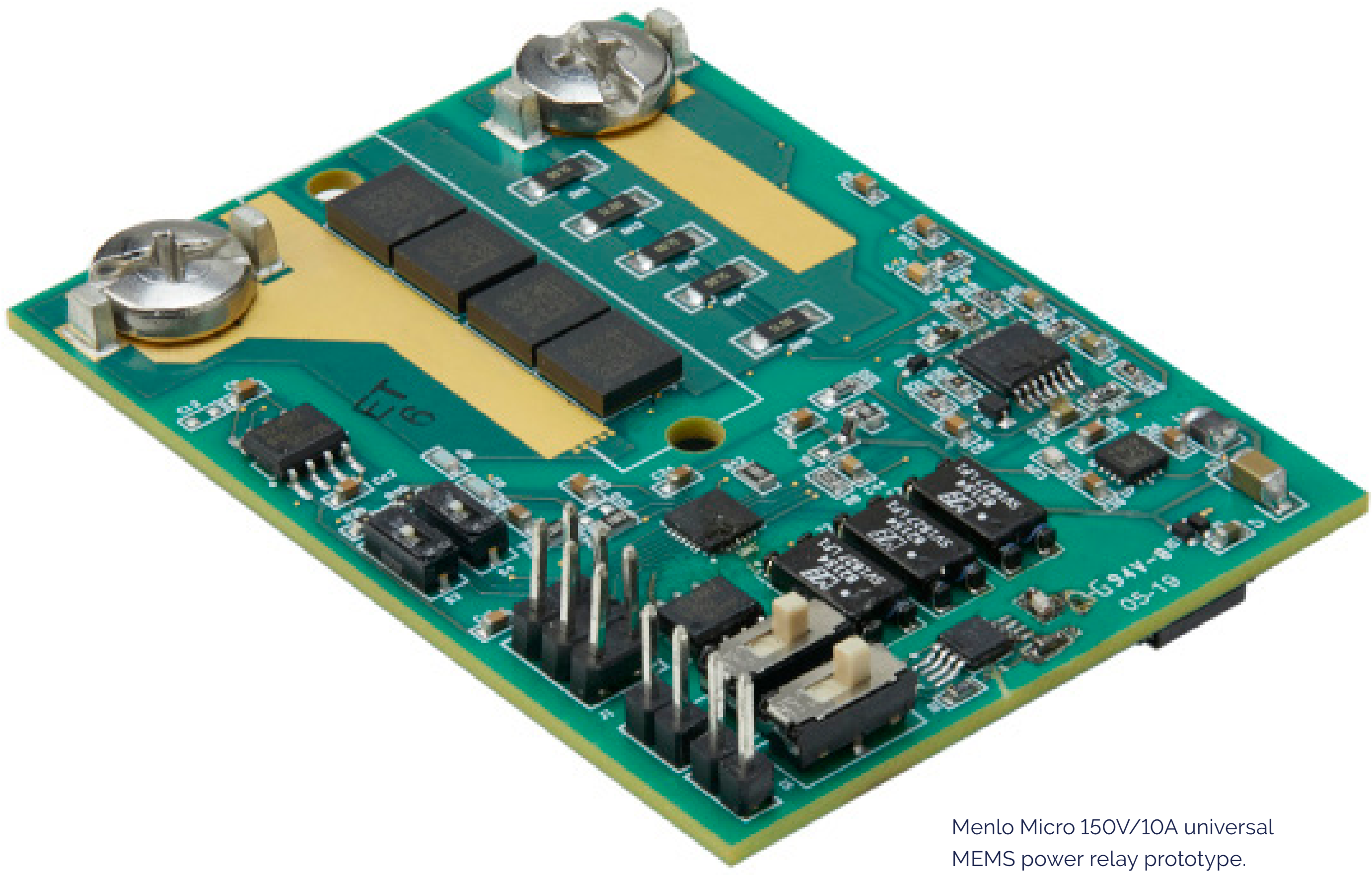
For example, a 100-switch matrix built with Menlo Micro's MM1200 device consumes 85% less space, 120 g less weight, and reduces the board height profile by 75%. Given Menlo Micro's reliability, it will also operate 300 times longer and reduce overall power consumption by up to 20 W. All these factors translate to significant SWAP-C savings at the system level and enable entirely new product form factors to be envisioned.

MM1200 with 6 micromechanical relays in a surface-mount package, compared to traditional 1-channel electromechanical relay.



A typical high-density switch card for test and measurement applications, with hundreds of traditional electromechanical relays.





Menlo Micro 150V/10A universal MEMS power relay prototype.

Smart Power Switching & Protection

Some of the applications originally envisioned by GE engineers will also soon be possible with switches being manufactured by Menlo Micro. The number of power relays, either solid-state or mechanical, being sold worldwide is in the billions. These power relays are unique as they need to handle very large loads, on the order of kilowatts and higher, and operate reliably for very long periods of time. Applications can range from electronic control relays to AC/DC contactors, and miniature circuit breakers, which are prevalent in markets such as industrial automation, battery management, automotive, home automation, and many others.

For example, Menlo Micro's Ideal Switch® technology is already proven to be scalable with a 240V/10A MEMS power relay prototype demonstrated in 2021. Testing shows that the technology can be pushed even higher. Some of the benefits exhibited in other market segments are true in the power sector as well. For example, ultra-low losses can eliminate the need for bulky heat-sinks, reducing size and volume by up to 90%. Fast switching speed and high reliability will make them stand out when compared to traditional mechanical relays and contactors. With the increased trends toward Industrial IoT and the "electrification of everything," the need for a miniaturized, low-power, and reliable power relay technology will continue to grow.

The Drive to Modernization

A strong, persistent drive exists worldwide to modernize power switching, control, and protection. This drive is across market segments. It is rooted in the need for better energy efficiency, forecasted energy demand growth, integrating distributed renewable energy resources, and deploying new technologies—while raising the bar on safe operation.

The forecasted energy demand growth is expected to impact electrical demand most with the wide adoption of electrical vehicles. While energy efficiency is driven by a need to lower the carbon footprint by reducing the baseload value. Baseload is generally addressed using fossil fueled power plants.

Penetration of renewable energy resources on the demand side creates the need to better manage these seasonal resources to maximize their collective impact in complementing, and where possible, decommissioning baseload generation. The emergence of IoT, IIoT and AI technologies offers the ultimate resources manager, while potentially creating opportunities for new revenue streams. This new highly interconnected, meshed electrical landscape is expected to complicate operation and maintenance of these new systems. Unless designed-in, safety could suffer in an already risk laden industry.

Whether it is safety, better efficiency, remote control or interoperability, all roads lead to more efficient and intelligent switching, by modernizing the most fundamental block: the switch.

The global nature of such a drive along with the cumulative nature of the solution, puts an astronomical price tag on these deployments. For the modernization solution to be adopted widely to be effective, there will need to be a carefully designed total cost of ownership.

The wide adoption of renewable energy (like electric vehicles) demands better management of electrical resources.

Power Switching Industries

Power switching, protection and control is deployed and used in every facet of modern society's economy. To segment the market, we look in terms of industries, segmenting the market into four verticals: Buildings, Industrial, Transport and Infrastructure.

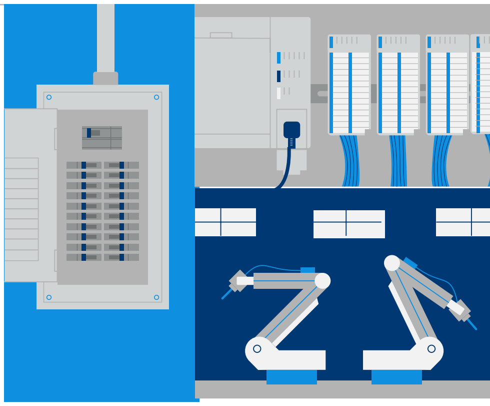
The buildings vertical is further divided into two sectors based on solution design and purchase decision making, these lead to two sectors: Residential Buildings and Managed Buildings. Switching solutions deployed in residential buildings tend to be incentivized by electrical utilities while designed and marketed following a consumer electronics lifecycle. On the other hand, managed buildings (e.g., commercial, industrial, airports, hospitals, hotels, etc.), follow a longer design and purchase lifecycle. Energy management in Residential Buildings is the utility domain, while the first layer of energy management in Managed Buildings is the Building Management Systems (BMS) domain.

The industrial vertical in turn, is divided into two sectors based on the type of production employed: Discrete and Process. Discrete industries include Automotive Manufacturing, Packaging, PV Manufacturing, Semiconductors, etc.) Process industries include Water & Wastewater, Pharmaceuticals, Oil & Gas, etc. The production sector defines the type of automation employed and in turn the sale cycle.

The transport vertical is divided into automotive (including EV), rail, marine and aviation. These sectors differ based on regulatory bodies and associated standards. Fuses and battery management switching are of particular interest for modernization.

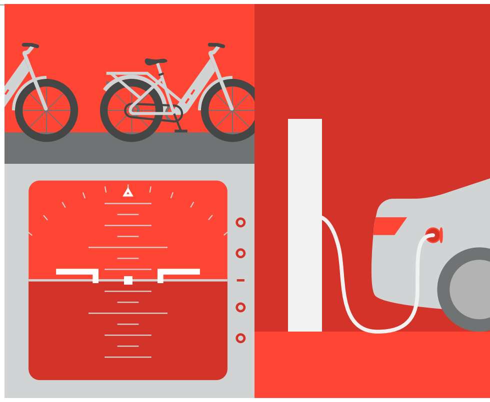
Industrial Automation

- Robotics & PV Manufacturing
- Automotive Manufacturing
- Food & Beverage Manufacturing
- Pharmaceuticals Manufacturing



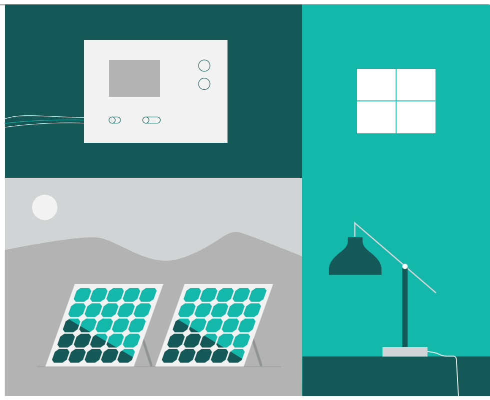
Transportation

- eMobility (EV, eBike)
- Battery Management
- Advanced Avionics
- Marine & Rail
- Electrification



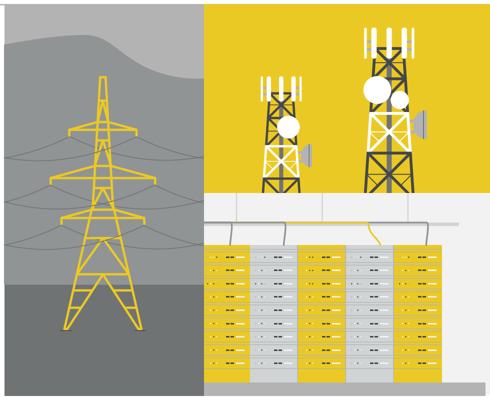
Buildings

- Commercial & Residential Micrograds
- Solar/Microinverter & Energy Storage
- HVAC and Appliance Controls
- Lighting/Smart Plug/GFCI



Electrical Infrastructure

- Power Grid, LV Switchgear
- Datacenter power distribution
- Communications equipment power distribution



The Specifications for an Ideal Switch® for Power Applications

The Ideal Switch® is uniquely positioned to be the modernizing building block when you compare its specifications to the electromechanical relay and the solid-state switch.

Actuation speed can directly affect safety by reducing the amount of energy discharge in the case of a fault or by reducing the steady state error in a feedback-controlled process.

Lower on-resistance, directly translates to less energy wasted in the form of heat, thereby considerably improving efficiency over solutions employing solid state relays.

A higher number of operations translates to longer operational lifetime of the switch; this results in the reduction in total cost of operation and the final cost of goods.

The size reduction offered by the Ideal Switch® enables retrofitting installed assets while adding needed modern functionalities in the same space, thereby accelerating the deployment of modern solutions.

Comparison of key specifications between technologies

	IDEAL SWITCH®	EMR	SSR	BENEFITS
Size	<2cm x 1cm x 0.2cm 0.4 cm^3 (no heat sink)	4.8cm x 3.5mm x 3.9mm 65.5 cm^3	4.5cm x 5.7cm x2.2cm 56.4 cm^3 (no heat sink) 225.9 cm^3 (w/heat sink)	• 99% reduction in volume • No heavy heat sink • Enables retrofitting installed assets with smart functions in legacy constrained space
Weight	<10 g	85 g	320 g	• 90% reduction in weight • No heavy heat sink • Streamlines supply chain cost
On Resistance	10 mΩ	100 mΩ	100 mΩ	• 10x reduction in resistance • Reduction in energy wasted as heat
Coil Power Consumption	<5mW	1.5W	<60 mW	• 80% reduction from SSR • 150x reduction from EMR • Additional energy savings on the control side
Turn on/off time	20/10 µs	15 ms	75/100µs	• 5x faster than SSR • >1000x faster than EMR • Reduces fault energy discharge • Reduces steady state error in a feedback controlled process
Lifetime	20B operations, decades of life	100k operations	>20B operations, decades of life	• 20kX more operations • Sizable reduction in total cost of operation and final COG

Carbon reduction

Reducing the number of coal-fired power plants is an employed tool in curbing the amount of CO_2 in the atmosphere. To this end, energy savings at the load are needed and can be achieved by either using a more efficient appliance or by implementing energy management schemes remotely, ideally both.

In addition to the savings achieved by the Ideal Switch® due to its lower resistance compared to solid state relays (SSRs), the Ideal Switch® enables the integration of communications and intelligence functionalities in a small package to replace the electromagnetic relay (EMR). These integrations enable implementing energy saving schemes at the load by adjusting operation time and length. The details of these automation schemes are dependent on the specific sector and segment within the vertical however specific, the Ideal Switch® enables automation schemes implementation at the local, mid, or central levels.

Ideal Switch® Impact

Generation Footprint

A reduction in power consumption equivalent to 120 coal-fired power plants globally over 10 years. This translates to reduction in green house gas emission of 1 $GtCO_2$ cumulatively over 30 years or by 2050.

Ownership Cost

Reduction in power consumption is expected to reduce the cost of building operations by saving $2 trillion in energy cost over 30 years.

Smart Building

The Ideal Switch's ability to integrate distributed intelligence, enables deployment and evolution of effective BMS (Building Management Systems) in commercial buildings.

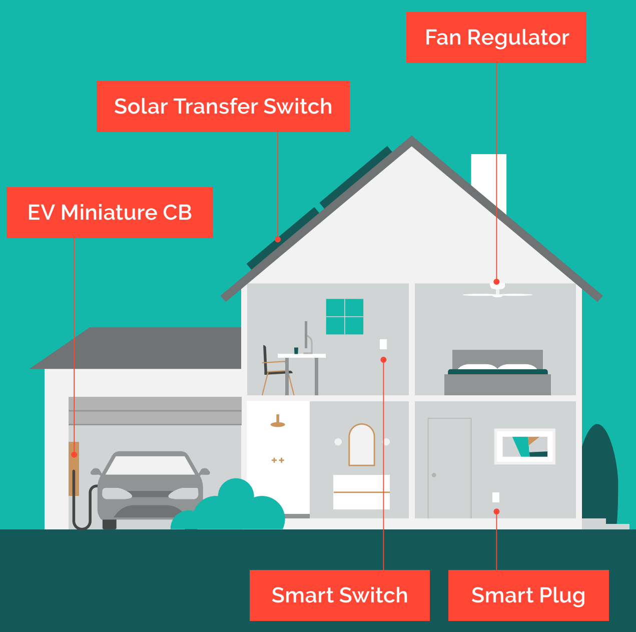
Smart Utility

The Ideal Switch's cost-effective and compact integration of connectivity enables the utility of the future to implement responsive grid policies for residential buildings. A key response to EV demand.

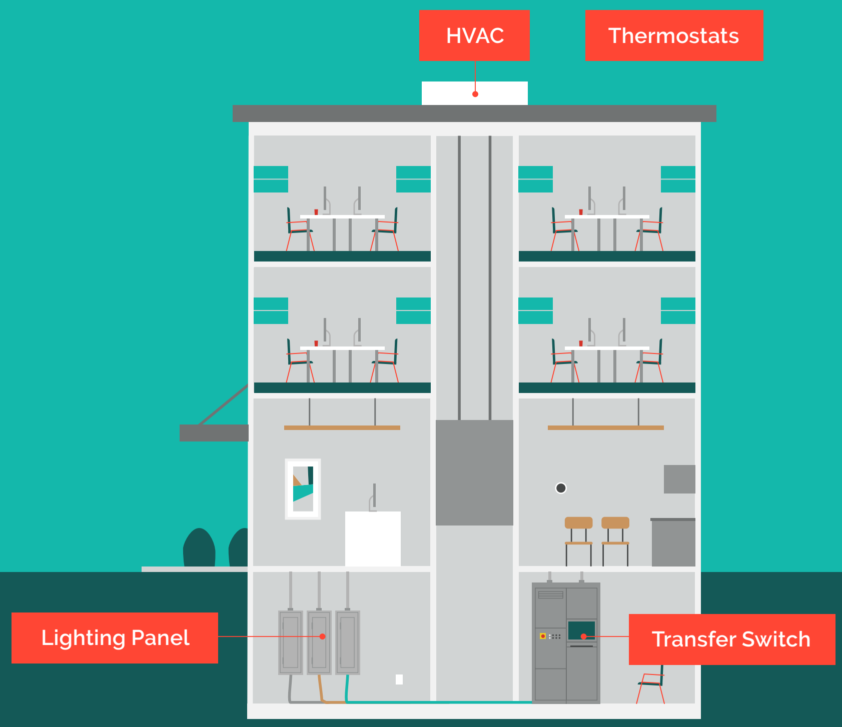
Impact on Buildings

Applications identified for the Ideal Switch® in the Buildings Vertical are extensive. Just some of those use cases include ceiling fan motor regulators, smart switching, smart plugs, miniature circuit breakers, molded case circuit breakers, air circuit breakers, HVAC, and transfer switches. Consider the first two applications under evaluation.

Residential



Commercial



Smart Switches and Smart Plugs

Smart switches and smart plugs are needed to enable various energy management schemes. These require a transition away from the current toggle switch and passive receptacle design to a switch with remote control. The switches currently used in the production of smart switches and smart plugs introduce an inefficiency due to leakage current and armature operation.

Per Table-1, we estimate a 2kWh savings per year per node if the smart plug and switch are implemented using the Ideal Switch as opposed to incumbent technologies. To evaluate the cumulative impact of such an implementation, we consider a global 10-year program to replace legacy toggle-switch and plug install base.

Since the US has 20 billion plugs installed, we assume half as much toggle-switches, totaling 30 billion nodes. One hundred per capita. If we assume a quarter as much per capita for the rest of the world, a 175 billion nodes install base can be assumed. A 10-year upgrade program will replace 17 billion devices per year. This is a total of ~35TWh per year. Which translates to ~10 coal-fired power plants per year (average power plant produces 3.5TWh per year).

Eliminating the need for 100 coal-fired power plants over 10 years stops the emission of 825 MtCO_2e cumulatively over 30 years i.e., by 2050. (5 MtCO_2e per power plant per year).

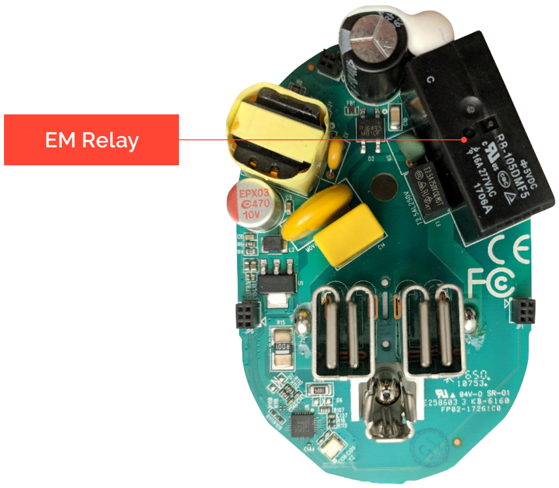


TABLE-1

Energy consumption for various smart switch implementations

	EMR	**SSR**	**IDEAL SWITCH**
Standby power	250mW	250mW	10mW
at 8000h/yr usage	2kWh/yr	2kWh/yr	0.080kWh/yr
Power losses in operation	400mW	320mW	40mW
at 2A, 1000h/yr usage	(100mΩR_{ON}) 0.4kWh/yr	(80mΩR_{ON}) 0.32kWh/yr	(10mΩR_{ON}) 0.040kWh/yr
Total Energy	**2.4kWh/yr**	**2.32kWh/yr**	**0.12kWh/yr**

Ceiling fan motor control

Ceiling fans are the primary method of climate control in many tropical countries and a secondary method elsewhere. In India, it is estimated that 500 million ceiling fans are installed consuming 8% of the electric power generated in the country, which equates to 100MtCO_2 emitted annually. A more efficient control of the ceiling fan's operation time and duration is bound to significantly improve the country's carbon footprint. Such an energy management scheme requires a connected or locally smart fan controller.

The fan AC motor speed is typically controlled by mechanical switching between different value capacitors or by using a Triac that shapes the AC feed.

The existing mechanical switching designs do not allow connectivity required to implement an automated energy management scheme. It also does not allow a microprocessor-based local management scheme. Modern connected controllers rely on a Triac-based design to execute a change of speed based on a local or remote energy management scheme.

The Triac-based design distorts the AC signal which leads to losses in the motor windings in the form of heat or sound.

Per Table-2, we estimate 45 to 60 kWh savings per year per fan if the fan speed regulator is implemented using the Ideal Switch® as opposed to current technologies.

In evaluating the cumulative impact of such an implementation, we consider a 5-year program to replace legacy fan controllers in India. 100 million fans retrofitted under this program will save up to 6TWh per year. **This translates to ~10 coal-fired power plants over the course of the program.**

A conservative assumption would be that the rest of the world has as many ceiling fans as installed in India, in which case globalizing such a program will double the savings to 20 coal-fired power plants. This stops the cumulative emission of 225 MtCO_2 over 30 years by 2050. (5 MtCO2e per power plant per year).

TABLE-2

Energy consumption for various fan regulator implementations

	EMR	SSR	IDEAL SWITCH®
Excess power consumption	15mW	10mW	150mW
at 3000h/yr usage	45kWh/yr	30kWh/yr	0.45kWh/yr
Grid losses due to poor power factor	—	10mW	—
at 3000h/yr usage	—	30kWh/yr	—
Excess Energy	**45kWh/yr**	**60kWh/yr**	**0.45kWh/yr**

Impact on Industrial Applications

The applications of the Ideal Switch in the industrial vertical are: Programmable Logic Controllers, Distributed Control Systems, Remote Terminal Units, Input / Output Modules, Motor Control Centers, soft motor start, Miniature and Molded Case Circuit Breakers.
Per Table-3, almost 8 billion devices will be shipped for these applications in factories in 2024.

We continue to conceptualize and evaluate the impact of each application. Consider the first application under evaluation, programmable logic controller (PLC) and input/output (I/O) modules.

Ideal Switch Impact

Longevity	A 2000 times increase in relay number operations over EMR, translates to $4 Trillion dollars in production cost savings.
Size	90% reduction in weight and volume compared to EMR and SSR heatsinks.
Fast Actuation	A 1000 times faster actuation in PLCs leads to a reduction in process steady state error. It also opens the field for a new class of PLC applications.
Arc Flash	Eliminates arc flash potential in motor control. This will lead to fewer operating injuries.
Ownership Cost	Compactness is expanded to reduce the cost of installation (CAPEX) while longevity will lead to fewer production interruptions (OPEX).

Segment Drivers

Automation

Energy Efficiency
- Supply Interconnection
- In-Process

Process Improvement
- Optimization
- Configuration

Supply Chain Efficiency

Electrical Safety

Distribution Protection
- Protection Relays
- Grid Reconfiguration

Arc-Flash
- Prevention
- Protection
- Mitigation

New Revenue Streams

AI
- Machine Learning
- Process-as-a-Service

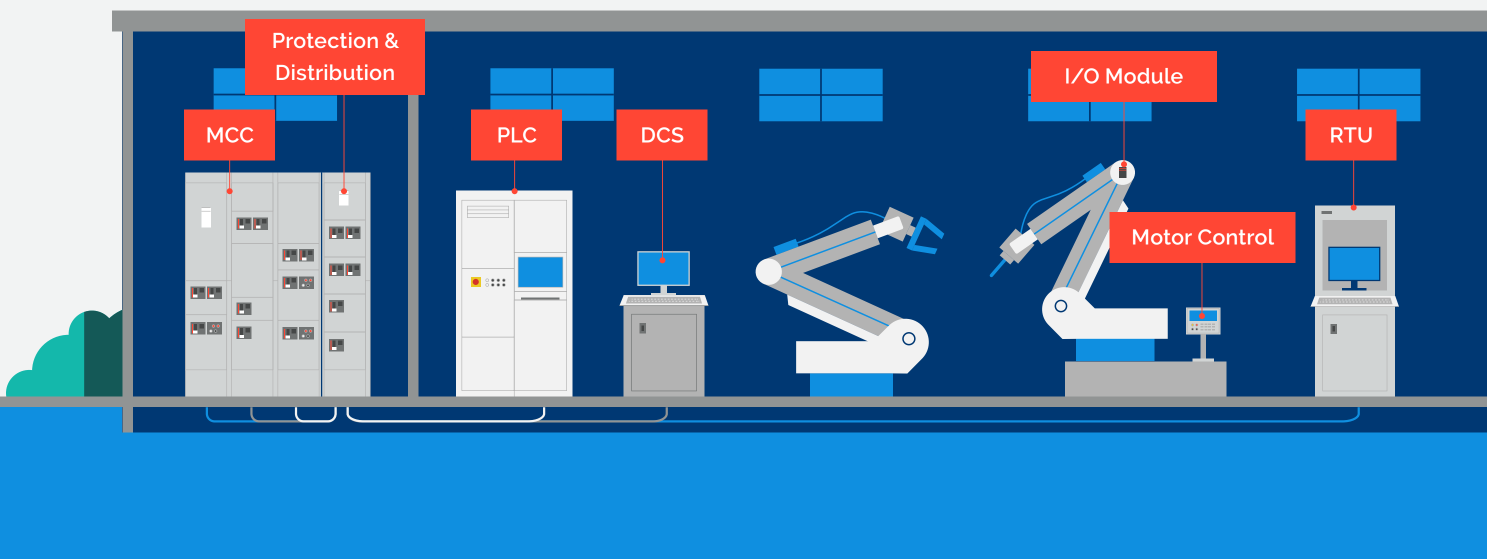
Energy Production

TABLE-3

Units shipped of end-products by application

(Source: Refer to Market Intelligence DB)

APPLICATION	SHIPMENT TO INDUSTRIAL VERTICAL (2024)
RTU: Remote Terminal Unit	720,000
PLC: Programmable Logic Controller	13,126,400
DCS: Distributed Control System	20,000
MCC: Motor Control Center & Soft Start	28,925,508
MCB: Miniature Circuit Breaker	1,045,373,130
I/O Module	47,317,459
Electromechanical Relay, Solid State Relay	6,447,662,864
ECR: Electronic Control Relay	65,605,978
Grand Total	**7,648,751,339**



Programmable Logic Controller & I/O Modules

In industrial automation, the fundamental building block for automation is an Input/Output module. This I/O Module connects to either a PLC for machine-level automation or a Distributed Controller System for a factory-level automation, and to a Remote Terminal Unit for human-machine interface.

The I/O module is an aggregation of appropriately rated and insulated relays, typically 4, 8 or 16 relays. While PLC, RTU or DCS head units normally come with a minimum of 4 I/O relays. From Table-4 we can calculate the average annual number of relays to be 400 million. The typical amortization of factory equipment is 25 years; we can estimate that there are 10 billion relays automating various manufacturing processes today. These relays are electromechanical.

Mean time between failures (MTBF) is the average time a device or component operates as expected before it requires maintenance or a replacement. For EMRs this time depends on the number of cycles the relay operates per hour. An accurate calculation of this key value is dependent on the manufacturing process. From Table-4 a typical EMR is rated for 100 thousand operations its maximum frequency is 6 operations per minute.

The Ideal Switch® is rated for 2 billion operations and a maximum frequency of 60,000 operations per minute. To estimate the cumulative impact of the Ideal Switch® on equipment and production downtime, we assume an EMR operates 1 time per minute on average which means a failure every 1500 to 2000 hours of operation, with 10 billion relays operating 24 hours, we expect 120 million relay failures per hour. You can expect the unplanned failures to reasonably be in the order of 1 in 106. This is 120 unplanned relay failure per hour.

If manufacturing switched to the Ideal Switch® for its relay implementation, a failure is expected every 600 million hours of operation, which translates to only 400 relay failures per hour globally. That is practically eliminating equipment downtime due to relay failures. It costs production on average $260,000 per hour of unplanned downtime,[1] and if it only takes 1 hour to diagnose, replace, and recommission a relay, that is an operational savings of $30 million per hour, $265 billion per year. Close to $7 trillion over the 25 years equipment ownership.

At Menlo Micro, we continue to conceptualize and evaluate the impact of the Ideal Switch® in each power switching, control, and protection application. While the initial segments analyzed include the Buildings and Industrial sectors, similar impacts will be uncovered as we expand our focus into the other verticals, including next-generation Transportation and Electrical Infrastructure as well.

TABLE-4

Typical I/O EMR ratings

(Source: Miniature Power PCB Relay MSR C23061)

CONTACT DATA

Contact arrangement	1 form C (CO) or 1 form A (NO)
Rated voltage	250VAC
Max. switching voltage	400VAC
Rated current, Versions A, B	8A
Rated current, Versions C, D	10A
Limiting making current, max 4s, df 10%	15A
Version A302, max 20ms	65A
Breaking capacity max.	2000VA
Contact material	$AgSnO_2$, AgNi90/10
Frequency of operation, with/without load	6/1200min-1
Operate/release time max.	10/5ms
Bounce time max., form A/form B	3/10ms

CONTACT RATINGS

TYPE	CONTACT	LOAD	CYCLES
IEC 61810			
V23061-A1***-A302	A (NO)	8A, 250 VAC, cosø=1, 85°C	$100x10^3$
V23061-C2***-A802	A (NO)	10A, 250 VAC, cosø=1, 85°C	$100x10^3$
V23061-C2***-A802	A (NO)	5A, 250 VAC, cosø=1, 150°C	$100x10^3$
UL 508			
V23061-A1***-A302	A (NO)	TV4, Tungsten, 120 VAC, 40°C	$25x10^3$
V23061-A1***-A302	A (NO)	PIlot duty, A300, 40°C	$6x10^3$
V23061-C2***-A802	A (NO)	10A, 240 VAC, general purpose, 40°C	$30x10^3$
EN60730-1			
V23061-A1***-A302	A (NO)	2(2)A, 250 VAC, 85°C	$100x10^3$
V23061-C2***-A802	A (NO)	2(2)A, 250 VAC, 85°C	$100x10^3$

[1] **DOWNTIME COST**

- In 2016, the average cost of downtime across all businesses was $260,000 per hour. (Source)
- In some industries, the cost is considerably higher; e.g. the auto industry, downtime can cost up to $3M per hour. (Source)
- It is estimated that factories lose 5% - 20% of their productivity due to downtime. (Source)
- Human error causes 23% of unplanned downtime in manufacturing. (Source)
- A 2017 survey found that 70% of companies lack complete awareness of when equipment is due for maintenance/upgrade. (Source)

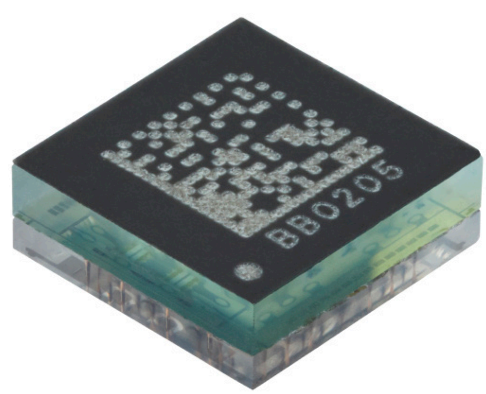
The Next Generation of Electrification: A Universal MEMS Switch

The electromechanical relay was introduced in 1835. The transistor in 1947. Both achievements enabled vast amounts of new technologies and products.

Comparing a phone from the 1950s to a smart phone today is probably the most dramatic example of the impact switches have. But cars, planes, trains, homes, offices, hospitals, factories, etc. have all seen massive improvements in safety-, comfort-, utility-, productivity-related technologies.

There is still room for existing switch technologies to drive enhancements, but they are incremental. To achieve true breakthroughs in telecommunications, transportation, and energy efficiency, we need a new type of switch. A switch that can handle both kilo Volts of power and GHz of RF signal, has zero loss thanks to a real airgap, and the linearity of a metal-on-metal relay. Menlo's Ideal Switch® can do all of this and is the size of a transistor manufactured affordably at scale in a semiconductor fab.

It is time for a new era of switches that improve today's technologies and enable entirely new possibilities in the future. A micro-mechanical universal switch has the potential to do that.



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