Technology Brief 25
Miniaturized Energy Harvesting

Energy is present in our environment in many forms. One can think of energy as a quantity that measures the ability of a system to do some amount of work on its environment (or other systems). For example, moving objects possess kinetic energy, objects within gravity wells possess potential energy, and charged particles within an electric field possess electrical energy. Real systems often ***transduce energy*** from one form to another as part of normal operation: photodiodes (solar cells) convert electromagnetic waves (light) into the movement of charge particles in a potential field (thus providing a system like your phone with the ability to do work), sensors often transduce chemical energy into electrical energy to measure the state of a system, an electrostatic actuator might transduce electrical energy into mechanical energy to perform mechanical work, etc. There is useful energy present all around you, in the gentle mechanical vibrations moving through your building, in the radio frequency waves generated by radio emitters, and even in the heat that your body or your car engine emits.

As computation and communication technologies miniaturize and become ever-more pervasive, many everyday computing objects require less and less ***power*** to operate. A typical circa-2012 laptop might consume 50–100 W (joules per second) during normal operation, a smartphone might consume 0.5–4 W (depending on what the user is doing, whether the radio is on, etc.), and a good low power wristwatch might consume 10 μW down to $\sim$100 nW.

As power consumption decreases for some functions, it turns out that there is, in many cases, just enough energy in the environment to power these systems. This is often known as ***energy harvesting*** or ***energy scavenging***. Below, we'll look at some interesting devices that have been built to scavenge energy from the environment to power everyday systems. A great many scavenging systems have been built in recent years, so we'll focus on general classes of scavenging. It is also important to note that the line between power scavenging and conventional power generation can become blurred: is a normal solar cell scavenging light to produce power? Sure! Is a wind turbine scavenging wind power to produce electricity? Of course. The idea is to focus on technologies that convert very small sources of power which, in the past, were often too small to be useful or were ignored.

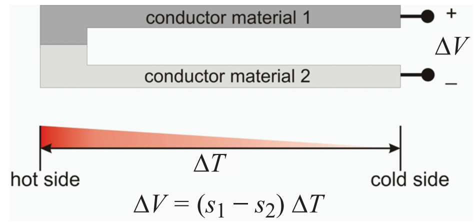

Figure TF25-1: The most common class of thermoelectric materials operate according to the ***Seebeck effect***. When two conductors are joined at one end and exposed to a temperature gradient (ΔT), a potential difference (ΔV) is measurable across the free ends of the two conductors. The relationship between ΔV and ΔT depends on $(s_1 - s_2)$, where s_1 and s_2 are the Seebeck coefficients of the two materials. The Seebeck coefficient is a material-specific property thet depends on the molecular structure of the material. This potential difference can be used to drive a current through an external load and thus do work. Interestingly, the effect can be run in reverse—known as the ***Peltier effect***—such that an applied voltage can be used to create a temperature difference. This is the basis of cryogenic cooling systems.

Thermoelectric

Almost every system that does useful work also produces heat. This "waste heat" is often exhausted to the environment but, since time immemorial, humans have also used heat to do work. Steam engines, internal combustion engines, the turbine systems at power plants and thousands of other ***heat engines*** extract useful energy from a heat source. Modern, top of the line power plants contain ***combined heat and power*** (CHP) systems that internally recover waste heat to increase efficiency.

A number of miniaturized technologies have been explored for scavenging tiny amounts of waste heat. Although these efforts have included making tiny heat engines, fundamental physical limitations have so far prevented successful scaling down of mechanical heat engines down to the millimeter. A different approach is to use materials that convert heat directly to electrical power; ***thermoelectric*** materials are in this category.

In the early 19th century Thomas Johann Seebeck observed that a voltage was induced when two dissimilar conductors were placed in a thermal gradient (**Fig. TF25-1**). Thermoelectric materials are used extensively to sense temperature. More recently,

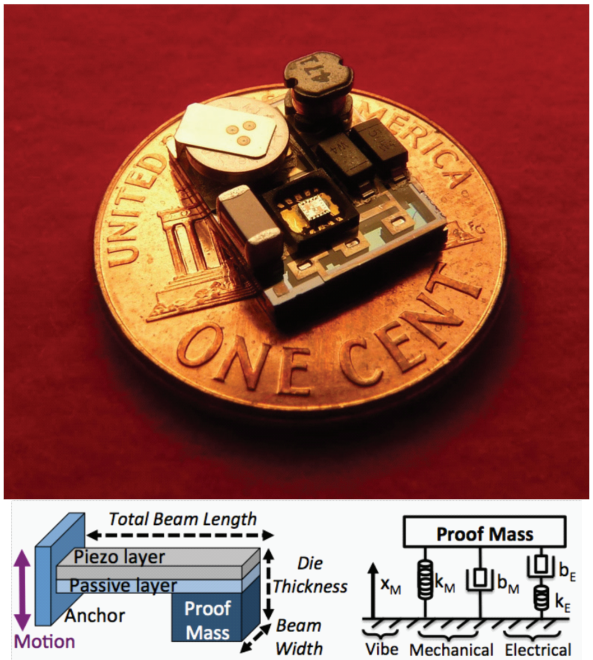

Figure TF25-2: (*top*) A tiny micromechanical harvesting system developed at the University of Michigan. It occupies 27 mm^3 and can harvest > 200 μW delivered at 1.85 V when exposed to 1.5 g's of acceleration when vibrating at or near ~155 Hz.

researchers have built tiny thermoelectric systems that scavenge power from small thermal gradients (such as is found between the surface of your skin and the environment); the small temperature difference (usually 1°–5 °C) and the low efficiency of existing thermoelectric materials has limited this to low scavenged energy densities ($<$1–10 mW per °C of temperature gradient per cm^2 of converter area) when compared to batteries or other conventional sources.

The efficiency of conversion (that is, how much of the heat energy is successfully converted to electrical power) hovers in the 1–6% range for implemented systems and this limitation comes from the thermomelectric material itself. A number of material-science efforts are under way to produce thermoelectric materials with higher efficiencies.

Mechanical Harvesting

A number of technologies have been developed to harvest the small motions present in everyday life. Perpetual motion watches use the regular motion of your arm to power tiny spring mass systems which either charge a battery or drive clockwork. Similar spring-mass systems (similar to those presented in Technology Brief 15: Micromechanical Sensor and Actuators) have been developed to power sensor motes deployed in areas with continuous environmental force or vibrations (**Fig. TF25-2**). As the environmental vibrations (which are usually very small, like those caused by the whirring of gears, the hum of an engine or the regular force applied by your heel to the rubber sole of your shoe) move the scavenger system, that force or motion can be converted to electrical power.

The conversion of mechanical work to electrical power can occur via the motion of charged conductor plates, electromagnetic windings or even a class of materials called piezoelectrics. A piezoelectric material converts mechanical deformation into a voltage or current (and vice versa as described in Technology Brief 19: Crystal Oscillators). Several technology development groups, for example, have introduced piezoelectric flexures to the soles of running shoes. The amount of energy scavenged depends on acceleration or force experienced by the system, but typical systems can range from ~1 μW/cm for normal vibrations encountered in daily life to ~ 100 μW/cm^2 in industrial or high impact settings (such as the vibrations given off by heavy machinery). **Figure TF25-2** shows an example of a complete energy scavenging system that employs a ***cantilever beam*** (the diving board structure in **Fig. TF25-2**) that acts as a spring with a proof mass at its tip. The cantilever structure oscillates when external vibrations are applied, deforming the cantilever. A piezoelectric film on the cantilever converts the oscillating mechanical energy to oscillating electrical energy that can power a circuit or sensor.

Radio Frequency Scavenging

A more recent class of devices attempts to scavenge power from the radio frequency electromagnetic energy. One common approach involves coupling oscillating radio frequency signals between (usually flat) conductive coils placed very close to each other; this is the basis of ***radio frequency identification*** (RFID) systems. A different approach is to collect or scavenge energy form electromagnetic energy present in our environment (from radio transmitters, phones, Wifi, etc.). Many working systems have been demonstrated in this second class over the years. One popular concept is the rectifying antenna, or ***rectenna***.