Self-Powered Processors

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Power has become a primary concern for computing systems ranging from embedded devices to massive data centers. Power consumption diminishes battery life, increases costs, and contributes to global warming. At the same time, ever-shrinking transistor dimensions promise to enable the manufacture of ever denser computing devices, yet powering those devices currently requires chemical batteries which are orders-of-magnitude larger or require sophisticated power supplies.

In this paper we suggest a completely different way of thinking about powering chips: make them self-powered. Self-powered chips leads to many interesting questions. How does one design systems with self-powered processors? What are the implications from embedded systems to data-centers? How would this change the economics of our industry? Processor manufacturers are also selling energy! And software systems developers need to worry less about power consumption! What are the implications of not having power distribution affecting the design? How would self-powered processors communicate with other parts of the system?

One can imagine a number of ways of making self-powered chips. Here we suggest two: (1) *embed a silicon generator inside the chip so it can draw energy from the environment*, and (2) *embed a tiny nuclear reactor to provide enough energy for the whole lifetime of the chip.* We justify their theoretical feasibility below.

Silicon: The first generator we propose is a variation of a standard silicon *p*-*n* junction (a diode). The device, which we call the Hammer-Anvil, absorbs the energy of the ambient heat around a processor to power the processor itself. The hammer-anvil works by absorbing heat energy and "wiggling" up and down. A piezoelectric device, which converts mechanical motion into electrical current, absorbs this wiggling to produce a current.

When *p* and *n*-doped silicon are brought together in a "closed-gap" configuration, charge carriers migrate between the two sides and reach a minimum-energy equilibrium state. A higher-energy equilibrium state can be constructed by separating the two regions, which prevents the migration of charge carriers and leaves the system in a higher-energy "open-gap" configuration. If the gap were closed, the open-gap system would relax to the lower-energy, closed-gap configuration, and the energy released could be extracted to do useful work. Usually, this transition would only happen once. However, if a device were constructed such that it oscillates between the open-gap and closed-gap configurations, then this small difference in energy could be extracted continually.

We have recently proposed such an oscillating device, and confirmed the presence of the electric fields (shown in Figure 1) and the energy differential between the open-gap and closed-gap configurations using Silvaco ATLAS device physics simulation software [1]. The hammer-anvil operates in a four phase cycle:

Charge: With the hammer and anvil separated, the electric field in the gap grows due to the thermal regeneration of charge carriers.

Attraction: As the field grows, the hammer is drawn to the anvil by the electrostatic force between the positive and negative charges.

Discharge: When the hammer touches the anvil, charge carriers flow, and energy is released as the system relaxes, and the attractive force diminsihes.

Recoil: At this point, the cantilever spring force overcomes the electrostatic force, and recoils the hammer from the anvil. After recoil, charge carriers use heat to regenerate charge carriers, re-establishing the gap electric field, beginning the cycle again.

Unlike solar cells, these devices can be stacked into cubes, making it possible to pack a much greater energy density onto the same footprint. Piezoelectrics typically have efficiencies between 50% and 95% at similar device sizes [2]. Assuming a 50% conversion efficiency, a 1mm^3 could generate 2.5W [3], enough energy to power an embedded processor. 40mm^3 could provide 100W, which could power a conventional desktop processor. Taken to the extreme, a 1m^3 block could provide 2.5 GW of power, enough to power a medium-sized city, though a device of this size would cool the room at a rate of 100^{o}C per second, and hence would stop working within a few seconds. These blocks could be sprinkled throughout the processor to eliminate outside power sources, and are small enough to power nano-scale computers and electro-mechanical systems.

Nuclear: The second device a variation of the NASA Stirling radioisotope generator [4]. The device converts heat, from both the processor and the decay of 1 gram of Polonium-208[1], into electricity via a Stirling converter. The generator measures 9cm *x* 9cm *x* 5cm (roughly the size of a modern heat sink), produces 53W of continuous power for roughly 5 years, and can be refueled easily. These generators can be stacked to provide greater generation capacity.

These devices represent a potentially massive shift in the way we power electronic devices, allowing portable systems to run almost indefinitely without recharging, and drastically reducing the cost of running large datacenters. Perhaps more importantly, these devices greatly enhance our ability to push computing devices to ever smaller dimensions, and to take advantage of nano-scale electromechanical systems.

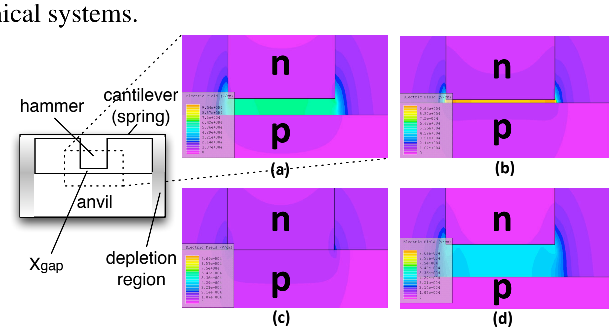

Figure 1: Hammer-Anvil device, shown on left. Zoomed in regions show E-field intensity (from 0 to 100 V/cm) for the region between the hammer and the anvil by phase: (a) Charge (b) Attraction (c) Discharge (d) Recoil. Device dimensions are 10μm x 6μm, with 1μm wide hammer. Doping concentration is 10^{-15} cm^{-3}

References

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[3] V. Capek and D. P. Sheehan, *Challenges to the Second Law of Thermodynamics*. Springer, 2005.

[4] A. Caponiti and J. Schreiber, "Advanced Stirling Radioisotope Generator ," U.S. Department of Energy, Tech. Rep., 2008.

[1] Two cheaper alternatives are also possible. Polonium-210 is more plentiful, but requires the generator to be refueled once every year. Strontium-90 is still cheaper, but requires an additional 1.04cm of lead shielding to absorb gamma rays.