Smart Dust

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Smart dust: *Self contained millimeter-scale sensing and communication platforms.*

Distributed sensor networks are all around us. Check under the hood and behind the panels in your car, inside the ventilation system in your office or lab building, or in the Westec boxes in a ritzy house in Beverly Hills. MEMS technology promises to make these networks cheaper, broader, and denser. Wireless technology is pushing in the same directions [5]. The cellular telephone network is a tangible example of the utility and feasibility of a ubiquitous wireless sensor network.

The ultimate physical limits and applications of distributed MEMS wireless sensor networks are still unknown. Some simple short range projections are possible however, based on existing technologies and devices. Smart dust is one such projection.

Concept

The system will be based around modulated corner cube reflectors (CCRs). Each element, or mote, of smart dust will contain a solar cell array, sensor, electronics, and CCR for communication. These dust motes will be distributed in the air or on the ground by the hundreds, or maybe millions. Projected cost per mote is about 10 cents, because the motes can be batch fabricated as monolithic units in standard, commercially available CMOS processes [10, 9, 7], and will not be packaged.

The distributed dust will be queried remotely by laser, each unit reporting its sensor information by modulating the reflected laser signal using a CCR. The sensor information might be current information (e.g. temperature and humidity in the littoral region), a summary of previous sensor information ("whatever I'm sitting on was vibrating two hours ago"), or merely an ID number for tracking material, products, et cetera. Communication *to* the dust is possible by modulating the laser.

Dust System Components

The following is a description of the subsystems carried on each millimeter square, 10 micron thick dust mote. There is nothing particularly "far out" about any of these subsystems. Most have been demonstrated in one form or another by other MEMS researchers.

Power

Power will come from an array of electrically isolated solar cells. Under bright sunlight ($1\mathrm{mW/mm}^2$), silicon solar cells will put out about 100 $\mu\mathrm{W/mm}^2$. Laser illumination can produce higher power densities, but a few tens of μW should be plenty. Klaassen et al. have demonstrated that arrays of electrically isolated N-wells can be created during electrochemical etching of CMOS chips [9]. Diodes made in these arrays can then be wired together in parallel or series to generate potentially large voltages (although at best tiny currents).

Thin film batteries [3] could be added to this system (during wafer processing) to provide some ability to operate at night, or at least to store information over night. A square millimeter of battery 10 microns thick would only store about 1 mJ of energy, but that is enough to communicate millions of bits using the corner cube, or for example run a wrist watch for many days.

Communication

Prototype MEMS CCRs have demonstrated communication at 500 bps over a distance of 1 meter [6]. 10 kbps data rates at less than 1 μW of power should possible with these first generation structures. Using something like Echelle's modulators [1] could get the data rate up above 1 Mbps with similar power dissipation.

Using good quality commercially available optics should bring the range over 1 km. With scanning lasers and smart CMOS imagers [8], it should be possible to simultaneously gather data from thousands of distributed motes, although probably at lower individual data rates.

Sensors

Sensor performance will be limited at microWatt power levels. Fundamental physical limits in the electronics will preclude extremely high performance, but many sensors will be able to function with a few tens of μW of power. These include sensors for sound (consider hearing aids/batteries), temperature, vibration, humidity, magnetic field, and many others. All of these have been demonstrated in standard CMOS (see, for example, Baltes [2]).

Electronics

The electronics, like the solar cells, will be fabricated in isolated N-wells. Devices demonstrated to date include PMOS transistors and vertical NPN BJTs [9]. This provides a sub-optimal but adequate working set. Fortunately, very little computation will be needed. The circuits will consist of an interrogation detection watchdog, analog sensor interface, sampling ADC, corner cube driver, and a simple state machine for scheduling. Power management will consist of leaving everything off most of the time, and turning blocks on one at a time to recognize a request and then acquire, digitize, and send the data.

Fabrication

Post CMOS processing by appropriate combination of electrochemical etching, RIE, and XeF_2 will yield the suspended solar cells, sensors, electronics (in suspended N-wells), and unassembled CCR attached to the wafer only through the dielectric/metal interconnect layers. These will be designed so that the entire system, including all of the sub-systems described above, is simply peeled off of the wafer surface. Prior to removal from the wafer, some sub-systems may need assembly. Specifically, the corner cubes will need to have their sides folded into the orthogonal position and locked. This will require automated micromanipulators with accuracy and motion comparable to existing automated wire bonding equipment.

Acknowledgment

The smart dust concept originated at a RAND workshop in December of 1992, inspired by Bob Zwirn's micro corner cube ideas, and Keith Brendley and Randy Steeb's report on Military Applications of MEMS [4]. It has evolved through several unrelated workshops sponsored by DARPA and NSF, most recently with strong influence from Andy Berlin of Xerox PARC. My thanks to those who have helped shape these ideas, and my apologies if I got it wrong.

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