Internet of Things: Sensing without power

A thermally activated micromechanical switch delivers an electrical readout signal only when irradiated by a narrowband mid-infrared light, thanks to a metamaterial element that converts light into heat.

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Sensor networks detecting rare events, such as a fire or an intrusion, must be both sensitive and selective, such that no important events are missed yet no false alarms are triggered. Using conventional sensing and electronic signal processing, constant vigilance and sophisticated discrimination ability come at the expenses of significant steady-state power consumption. To address the growing need for ubiquitous autonomous intelligent sensing for the Internet of Things requires a rethinking of this tradeoff. Writing in *Nature Nanotechnology*, Qian et.al.[1] now show a micromechanical signal transduction to create an infrared light sensor that achieves high sensitivity and optical wavelength selectivity while consuming no electrical power. The sensor operates in the thermal, mid-infrared region of the optical spectrum. The detected radiation energy actuates a micromechanical relay, providing a digital (on/off) electrical readout.

In the absence of the infrared signal of interest, the relay contacts remain open, and no power is consumed. When as little as 500 nW of infrared light within a specific, predetermined narrow wavelength band hits the device, the optical energy is absorbed, converted into heat and used to mechanically close the contacts, forming a low-resistance electrical connection. Multiple devices sensitive to different mid-infrared wavelengths can be fabricated side-by-side and their on/off outputs logically combined by connecting them in simple serial (AND) or parallel (OR) circuits for more complex operations, in which only a spectral signature triggering the correct sensor combination would close the circuit.

Compared to semiconductor technologies, micromechanical relays can have near-zero steady-state power consumption, with very low leakage current in the open state and extremely sharp transitions with high on/off ratios. These devices have been successfully used in the radio-frequency regime, motivating research in extreme low-power digital signal processing in other frequency ranges [2]. Qian et al. have shown that micromechanical relays can respond to mid-infrared light. Three distinct technologies are cleverly combined to achieve this – plasmonic metamaterial absorbers, microbolometers and thermally-actuated micromechanical switches – sequentially coupling optical, thermal, mechanical and electrical domains (Figure 1).

Wavelength-selective energy harvesting is accomplished by a thin plasmonic metamaterial – an array of closely spaced, lithographically patterned subwavelength structures, each supporting a resonance at the desired absorption frequency (Fig. 1A, C). The array period is tuned to optimally couple the incident light to the resonators, obtaining near-unity absorption efficiency by matching the optical impedance between the plasmonic metamaterial and the free space. Multiple sensors with distinct absorption bands are fabricated side-by-side by lithographically varying the metamaterial pattern.

The resonance occurs when gap plasmons inside a dielectric- gap between two metal layers are laterally confined by patterning the top metal to form an in-plane standing wave. Such resonators have been shown to be remarkably versatile: changing their lateral size can tune the resonance frequency across a very broad range, from visible to thermal infrared, while changing their shape introduces polarization selectivity and affects coupling to free-space radiation. In the near-infrared, resonances of higher lateral order are much sharper, reaching the intrinsic limits set by the metal loss[3] – a possible opportunity to improve the wavelength discrimination by 3x or more. The lateral size scales with gap size, enabling strong coupling of 10 nm gap nanoscale plasmon resonators to nanomechanical systems[3]. Engineering the resonator's size and shape may lead to customizable, spectrally-complex and highly-efficient metamaterial absorbers.

The harvested energy is then converted into motion (Fig 1B). To do this, the device is thermally isolated by suspending it in vacuum on long, narrow and low-thermal-conductivity supports, trapping the heat and converting it to a temperature rise. This microbolometer approach is widely used in thermal imaging camera pixels; however, instead of a power-hungry electrical measurement of temperature, mechanical motion is generated by differential thermal expansion of a bimorph structure formed from two dissimilar materials connected to the metamaterial element. The bimorph curvature changes with temperature, moving the tip vertically to close the contacts. High sensitivity is achieved: $\approx$ 500 nW changes the temperature by less than 1 °C, enough for a 400 μm long Al/SiO_2 bimorph to close a 0.5 μm gap. Since a single bimorph is also sensitive to an ambient temperature change, Qian et.al., improving upon previous research [4,5], implement a micromechanical reference mechanism for a double-differential transduction to cancel out motions unrelated to the absorbed radiation.

Exploiting mechanical motion for sensing has a long history: coupling motion to radiation through pressure and thermal effects goes back to the first light-pressure measurements at the turn of the 20th century. Micro- and nano-mechanics improve coupling strength, sensitivity and response time by exploiting wavelength and sub-wavelength scale photonic and plasmonic resonators, with the best sensors operating near fundamental thermodynamic and quantum noise limits. Batch-microfabrication and dense integration of many devices at almost zero additional cost presents new opportunities for gathering and processing information for applications such as unpowered thermal imaging sensors for detecting spatial as well as spectral signatures. Adding electrostatic relays can implement NOT gates for arbitrary logic, while adding electrostatic actuation to the current devices may enable controlled latching, extending the discrimination ability into the time domain, yet still without requiring any steady state power. Notably, this type of near-zero-power sensing and discrimination paradigm can, in principle, be extended beyond optical signals, to many physical quantities that can be transduced into motion.

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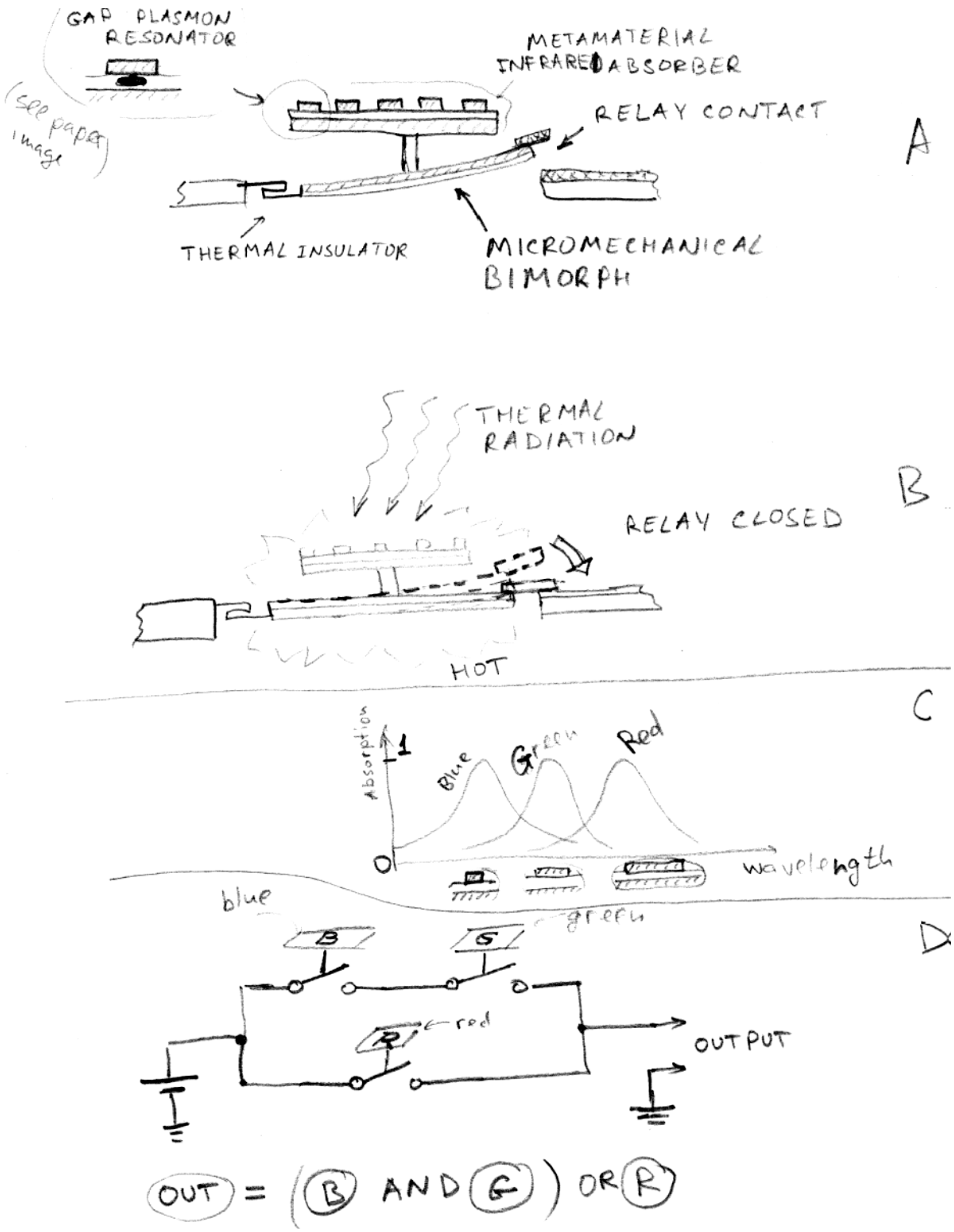

Figure 1: Passive mid-wavelength infrared detector (a) combines a plasmonic wavelength-selective absorber, a microbolometer and a thermally-actuated micromechanical relay. (b) Absorbed thermal radiation energy closes the relay. (c) Localized gap plasmon resonator size tunes the absorbed frequency for spectral selectivity. (D) multiple passive detectors form logic circuits.