APPLIED PHYSICS

Nanothermal trumpets

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The thermal process known as Joule heating, which often plagues electronic devices, has been turned to good use: making devices that can produce sound as well as reproduce music and speech.

James Prescott Joule, the nineteenth-century British physicist whose research on electricity and heat led to the first law of thermodynamics, is eponymous with Joule heating. This is the mechanism by which an electrical conductor converts electrical energy into heat. Joule heating has always been considered an inevitable loss term for the efficiency of electronic devices, except for domestic appliances such as electric heaters and cookers, which rely on it to function. Writing in *Applied Physics Letters*, Niskanen *et al.*[1] describe how Joule heating can be exploited to make efficient and controllable sources of sound.

The idea of converting Joule heating into sound is nearly a hundred years old. It was first proposed[2] by Arnold and Crandall, who called their sound devices thermophones. But progress in turning such thermoacoustic machines into efficient sound sources has been hampered by the high thermal conductivity of the metal wires (the electrical conductors) and of the supporting structure on which the wires are hinged or laid. Under these limitations, any Joule heat produced by the metal wires would leak out and therefore not contribute to the large temperature variation in the device that is required to produce sound.

Niskanen and colleagues' sound devices[1] consist of an array of parallel aluminium wires — as many as 200,000 wires in an area of a few square centimetres — suspended over a silicon substrate. The wires are clamped at their ends to aluminium crossbars using standard silicon microelectronic processing techniques. Each wire is about 200 μm long, 3 μm wide and only 30 nm thick. Using electric-power levels of 17 W, the authors demonstrate sound levels of more than 100 dB at a frequency of 20 kHz and a distance of 7 cm from these microscale sound sources. Such sound levels are impressive for thermoacoustics but considerably smaller than those obtained in conventional home and rock-concert speakers, which can blare out sound at 100 dB for 1 W of electric power to a distance of 1 m. Even so, Niskanen *et al.*[1] show that their devices can reproduce music and speech.

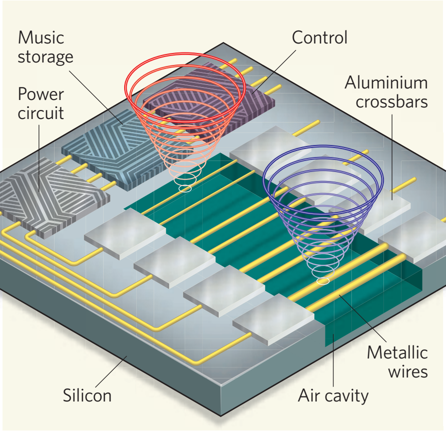

Figure 1 | A thermoacoustic integrated device. Niskanen and colleagues' sound device[1] is based on an array of parallel wires, nanometres thick, suspended over a silicon substrate and clamped at their ends to aluminium crossbars. It could be modified to incorporate further elements such as music-storage and control electronics. In this example, the array consists of several pairs of wires of different width, producing sound of different pitch (as denoted by the blue and red sound wavefronts). A power circuit supplies the array with electric power and causes temperature variations in the surrounding air that in turn generate air-pressure variations, and thus sound waves. A control element can either allow music to be stored or provide input directly to the power circuit. (Device not to scale.)

The mechanism that underlies sound production in the authors' devices[1] is, although similar in fundamental origin, unlike that of a musical instrument such as a trumpet, in which sound is produced by an air-pressure wave set up by the musician blowing into the instrument's mouthpiece. Instead, their devices — let's call them 'nanothermal trumpets' — generate sound by means of temperature variations in the air surrounding the wire array. These air-temperature variations are induced by Joule heating in the wires when electric power is applied to the device, resulting in time-dependent air-pressure variations, and hence sound.

The low thermal conductivity required for the wires' support structure, which Niskanen and colleagues take advantage of in their experiment, was first achieved by Shinoda and colleagues[3]. These workers used an aluminium film on porous silicon, which had a thermal conductivity 1/168th that of crystalline silicon, to produce ultrasonic emission of frequencies up to 100 kHz. Later work by Xiao *et al.*[4] showed that ultrathin films of carbon nanotubes can be used to create loudspeakers over a wide range of frequencies. All these devices[1,3,4] have similar characteristics, being dependent on power and frequency and independent of crosstalk between adjacent wires. However, because it is fabricated on a silicon wafer, Niskanen and colleagues' device will allow control and memory electronics to be integrated into it (Fig. 1). It could store music on a memory chip integrated on the same wafer, direct sound waves at a desired angle using 'phased arrays' of wires, and allow sound-wave interference in a particular pattern.

Progress in the field of thermoacoustics may be boosted by advances in the sister field of thermoelectrics, which seeks to use what is known as the Peltier effect to develop materials that efficiently convert heat into electricity, or vice versa. The past decade has witnessed a resurgence[5–8] of interest in this field. Although much of the work was aimed at reducing the thermal conductivity of semiconductors, there has also been growing interest in thermal transport in nanoscale metallic structures[9]. The thermal conductivity of ultrathin (less than 100 nm) metallic films has been predicted to be much smaller — more than a factor of five smaller for a 30-nm-thick film such as that used by Shinoda *et al.*[3] and Niskanen *et al.*[1] — than that of bulk structures (those thicker than about 1,000 nm).

The physics underlying the use of nanoscale metallic structures for thermoacoustics is not fully understood. Niskanen and colleagues mention the possible use of miniaturized thermoelectric coolers in their devices, presumably for additional temperature control. It would be worth considering making the metallic wires themselves out of a thermoelectric material, or cooling and heating the two ends of the wires with on-chip thermoelectric devices, thereby exploiting not only Joule heating but also Peltier heating and cooling. And the successful incorporation of nanoengineered thermoelectric devices onto silicon chips[8] indicates that such devices could be used to develop thermoacoustic integrated circuits.

Detailed knowledge of the thermal properties of nanoscale materials, complemented by modern techniques for fabricating materials and creating devices, will undoubtedly bolster research and development in thermoacoustics. Arnold and Crandall could hardly have imagined such achievements in the field nearly a century ago, and Niskanen and colleagues' sound source would undoubtedly have been music to James Prescott Joule's ears. ■

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