Wearable electronics

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Compound semiconductor devices for the skin

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Nanomembranes of GaN grown by remote epitaxy form the basis of surface acoustic wave sensors in wireless electronic skins for health monitoring.

Remote, continuous monitoring of physiological parameters during natural daily activities will overcome shortcomings associated with traditional episodic assessments performed during visits to clinical facilities. The results will define a digitally enabled future for healthcare that involves not only treatment but also prediction of disease. Skin, the largest organ of the human body, serves as a powerful, non-invasive interface for capturing a wide range of parameters related to health status, from characteristics of cardiopulmonary activity, to hydration status, core body temperature and blood oxygenation. Rapid engineering advances built on emerging capabilities in materials science serve as the basis for ultrathin, ultrasoft, 'skin-like' devices that can measure these and other quantities with clinical-grade accuracy, without constraint or discomfort and at any anatomical location[1]. Analysis of large datasets generated by such technologies will provide actionable insights to enhance the care of patients, with improved outcomes at reduced costs.

Developments in materials science and methods for heterogeneous materials integration are critically important to realizing this vision. Here, ideal device attributes can be realized through combinations of hard and soft materials in patterned layouts that yield high-performance systems with elastic properties, thicknesses, areal mass densities, thermal properties and water vapour transmission characteristics comparable to those of the epidermis, for integration with the skin in a manner that is imperceptible to the patient. Some of the most successful strategies exploit semiconductor nanomembranes (NMs) as functional elements of the sensors and associated electronics[2]. Developing routes to synthesizing and manipulating such NMs represents an active, dynamic area of materials research. Past schemes rely primarily on anisotropic chemical etching of thin layers of material from bulk wafers[3], selective elimination of sacrificial layers in multilayer assemblies[4] or laser-induced layer transfer[5]. Although well developed for monocrystalline silicon and certain compound semiconductors such as GaAs and GaN, some of these techniques require multilayer structures and others lead to damage at the surfaces of the NMs and/or the underlying growth substrates. A relatively recent method, known as remote epitaxy, developed in 2017[6], offers a versatile set of capabilities that address these challenges. This powerful technique creates semiconductor NMs by growth on a wafer substrate coated with a monolayer of a van der Waals material, typically graphene, followed by mechanically induced removal and wafer re-use.

Recently, writing in *Science*[7], Kim and colleagues reported that they have exploited this route to GaN NMs as the basis for surface acoustic wave (SAW) sensors in systems that can gently mount on the skin for wireless, battery-free recording of key health-related parameters (Fig. 1a). Specifically, release and transfer of GaN NMs from graphene-coated wafers of GaN to thin polyimide substrates followed by photolithographic patterning of interdigitated conducting traces forms SAW sensors in freely suspended layouts. Electrical interconnects and adjacent antenna structures in serpentine-inspired geometries (that is, an auxetic dumbbell hole pattern) ensure stretchability, and thus skin compatibility, for the completed systems. Perforations further enhance the mechanical compliance and also ensure breathability to accommodate transepidermal water loss. Radio-frequency electromagnetic power from an external antenna placed next to such a device couples through the integrated antenna into the GaN NM, to launch SAWs (Fig. 1b) via the piezoelectric effect. The resonant frequencies of these systems, determined wirelessly through the same external antenna, depend on various properties of the surroundings with a sensitivity governed by an electromechanical coupling parameter (k^2). The suspended layouts, the high-quality, single-crystalline properties and the thin geometries of the GaN NMs lead to extremely high values of k^2, as in Fig. 1c. The authors demonstrate their wireless device in a range of interesting sensing modes. In one case, the device responds to mechanical strains via the piezoelectric effect, to enable real-time monitoring of pulsatile blood flow in near-surface arteries of the wrist (Fig. 1d). Other examples involve selective measurements of ions in sweat and of exposures to ultraviolet light.

These advances represent important steps towards skin-interfaced electronics that incorporate compound semiconductor NMs, with

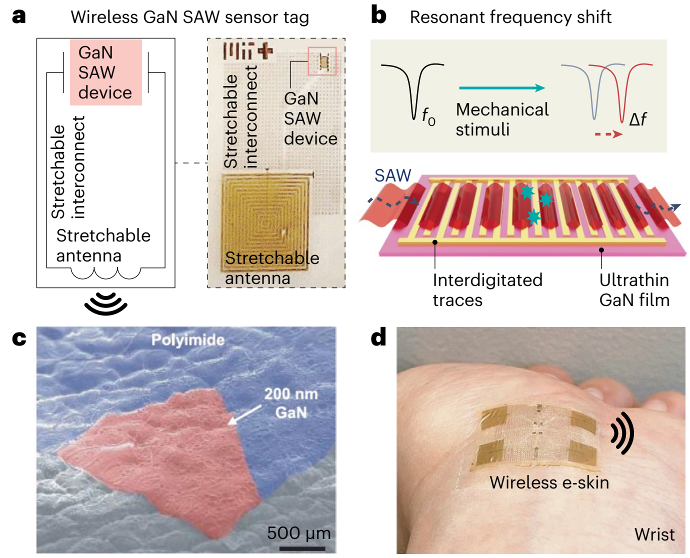

Fig. 1 | NMs of GaN for wireless, skin-like sensors based on SAWs. a, Circuit diagram and photograph of a wireless, stretchable electronic device that integrates a SAW sensor based on a GaN NM. **b**, Schematic illustration of the working principle of the SAW sensor. **c**, Scanning electron micrograph of a GaN NM (200 nm thick) on a skin replica. **d**, Photographs of a device mounted on the wrist for wireless monitoring of pulsatile blood flow through a near-surface artery. Panels **a**, **c** and **d** reprinted with permission from ref. [7], AAAS.

the exciting potential to expand beyond GaN to many other classes of NMs that can be synthesized by remote epitaxy. The specific classes of wireless sensors built on SAW responses are also of interest. The passive designs are appealing because they avoid the need for integrated circuits or batteries, but limitations in communication range (currently ~14 mm in the *z* direction) may be significant for many applications. Opportunities to combine these approaches with active radio communication capabilities and strategies for power harvesting that have been used in previous forms of epidermal electronics based on silicon NMs[8], microdie integrated circuits[9] and/or organic electronic materials[10] appear to be promising. Such materials and hardware advances, taken together with progress in artificial intelligence and edge-computing resources, will accelerate the transition to quantitative, data-driven paradigms in healthcare, with the strong potential for wide-ranging societal benefits.

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Competing interests

The authors declare no competing interests.