[Section number] – Quantum photonics and lightwave electronics

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Status Optoelectronics stands on the cusp of a major transformation through the integration of layered materials (LMs) [1-3]. These herald a new era of solutions to pressing issues, including the quest for energy sustainability. They can significantly boost the efficiency of both information and communication technology (ICT) and light harvesting, as well as providing energy-efficient resources for artificial intelligence (AI). Concurrently, LMs are poised to thrust quantum information science and engineering (QISE) into a realm of practical usability, offering unprecedented performance advantages over classical options. Here, we highlight recent ideas and advances for energy solutions, AI, and QISE based on graphene, semiconducting LMs, and their heterostructures (LMHs).

Graphene can provide advanced functionalities in key technological devices and is the most mature of the LMH technologies. It already has delivered competitive energy efficiency and speed for devices such as low-power and hyperspectral photodetectors useful for autonomous driving, and modulators integrated in silicon-photonics, outperforming the state of the art [2]. Emerging applications include photosynthetic devices, LiDAR, security, and ultrasensitive physical and chemical sensors for industrial, environmental, and medical technologies.

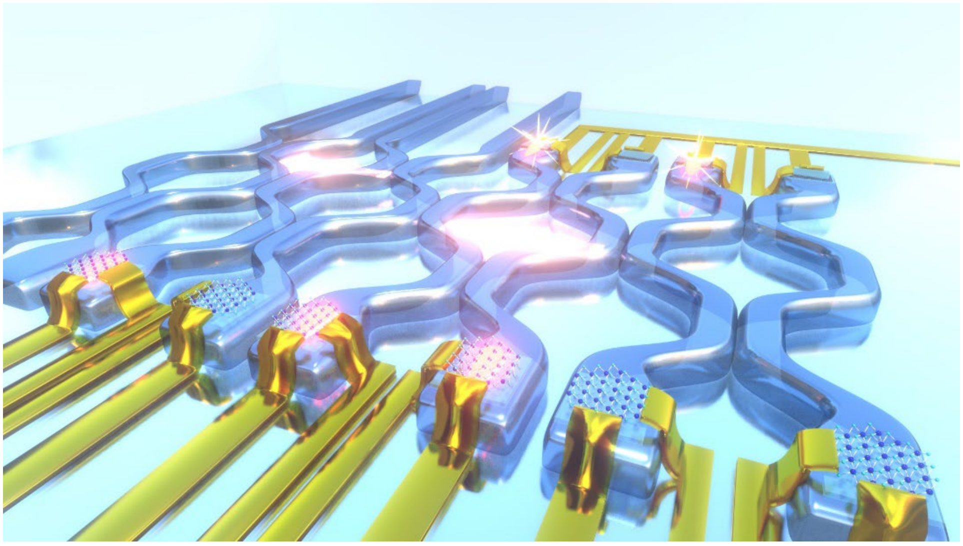

Figure 1 | Scalable integrated photonics. Scalable integrated photonic circuits built from on-chip quantum devices using critically coupled LMHs, adapted from A. R.-P. Montblanch et al., Nat. Nanotechnol. 16, 555–571 (2023).

Twisted LMs have provided promising new directions for AI devices. Asymmetric potential and ferromagnetic switching in twisted bilayer graphene (t-BLG) were used to achieve synaptic behaviours for neuromorphic computing functions [4,5]. By leveraging tuneable quantum geometric properties of t-BLG and advanced AI algorithms, intelligent sensing of high-dimensional optical information with a single on-chip sensor was demonstrated [6]. Recently, LMs have been configured to mimic the dynamics of biological synapses [7], heralding a new generation of energy-efficient AI hardware.

Semiconducting LMs are currently evolving fast as a new platform for quantum technology. They have already shown potential as scalable components, such as quantum light sources, photon detectors and nanoscale sensors, and enabled new materials discovery within the broader field of quantum simulations. Yet, harnessing quantum information *within* semiconducting LMs has remained challenging when operating at GHz clock speeds because each electron scattering event—occurring roughly 10^4 times per GHz cycle—terminates quantum operations.

Lightwave electronics addresses this critical QISE barrier by using the oscillating electric field of intense optical carrier waves as ultrafast biasing fields, enabling quantum operations that outpace the oscillation cycle of light [3]. As illustrated in Fig. 2, lightwave electronics can transport electrons coherently at petahertz (PHz) clock speeds—one million times faster than conventional electronics and 100 times faster than scattering occurs—and flip quantum states within a few fs [8,9] under ambient conditions. Utilizing a quasiparticle-collider setup shown in Fig. 2, such quantum operations have been timed with attosecond precision to access delicate multi-electron interactions and correlations within LMs, providing direct access to electronic entanglement states. These breakthroughs have set the stage for meaningful QISE advancements that will enable quantum sensing, communication, and transduction applications, and augment classical electronic and photonic devices with entanglement capabilities.

Current and Future Challenges

The intrinsic confinement of electrons within LMs leads to minimally screened interactions that synergistically enhance the coupling between light, charge, lattice vibrations, and spin states. By crafting LMHs, electrons can be confined, transported, and topologically altered across desired layers—unlocking new functionalities and broadening the design landscape. However, many demonstrations are still based on manually constructed, micro-scale materials. Wafer-scale growth of LM and LMHs is the next challenge.

Realizing PHz and entanglement electronics (Fig. 2) requires overcoming several escalating challenges: conducting single operations swiftly enough to surpass electron scattering events (1-fs timescale), generating a sequence of such operations, ensuring high-precision timing and control (100-as timescale), and chaining multiple operations to leverage coherent, correlated, or entangled electrons for QISE applications. Although significant progress has been made, further innovations, particularly in sequencing and chaining operations, are necessary. To achieve these stringent goals, lightwave electronics could utilize short, asymmetric lightwaves that impart net, directional momentum onto electrons. This necessitates the development of flexible and stable methods to generate arbitrary waveforms, akin to DC pulses. Integrating lightwave sources into the devices themselves is critical for improving efficiency and reducing costs, a goal that could be facilitated using photonic structures that guide and focus light and plasmonic nanostructures to enhance electric fields.

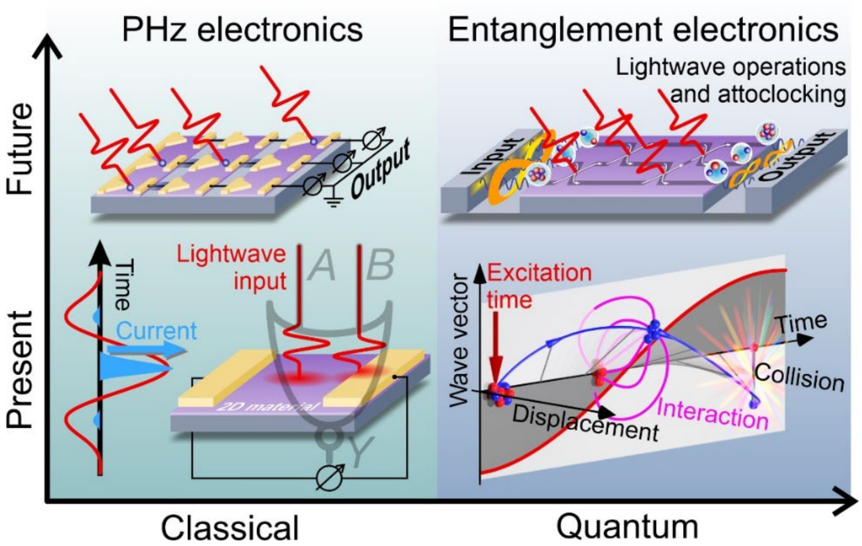

Figure 2 | Vision of lightwave electronics. Strong lightwaves can *nonlinearly* and coherently excite directional currents, following the main peak of few-cycle pulses (inset, lower left). This principle has enabled basic logic-gate operations (lower left, schematic; adapted from Ref. [9]) using the carrier-envelope phase of two pulses as inputs (A and B) and the output (Y) encoded in the current between electrodes, laying the groundwork for PHz electronics. Future directions could include building an entire PHz processor (top left) by integrating hybrid multi-electrode–lightwave arrays. Lightwave-operated quasiparticle colliders can directly detect and drive multi-electron correlations (spheres) by attoclocking excitation-to-collision timing (lower right; adapted from Ref. J. Freudenstein et al. Nature 610, 290–295 (2022)). Advances could improve excitation, control, timing, and readout of multi-electron correlations in LMs (top right; adapted from Ref. [3]) by chaining multiple quantum-state operations within the lifetime of coherences for entanglement electronics.

A combination of theoretical investigations and advanced quantum spectroscopic tools will be essential for directly accessing QISE-relevant correlations. At present, both theory and experiment face significant challenges. Multi-electron predictions are computationally prohibitive, and flexible and robust sources and detectors for complex quantum states of light remain elusive. Developing such predictive tools and technologies would be crucial for leveraging quantum states for various applications.

Advances in Science and Technology to Meet Challenges

While promising progress have been made for wafer-scale synthesis of graphene, hBN, and transition metal dichalcogenides (TMDs), many applications in energy, AI, and QISE demand LMHs consisting of a variety of LMs with diverse physical properties. Since different LMs can require distinctive synthesis conditions, it is challenging to directly synthesize the desirable LMHs on demand. As a result, future technologies will require both wafer-scale synthesis and autonomous/robotic and Ai-assisted transfer techniques [10] for the preparations of wafer-scale LMHs on demand. Successful integration of LMs into existing electronic and silicon-photonics platforms is also paramount.

Lightwave electronics has also been extended to the videography of single-electron dynamics [3] by combining near-field techniques with attosecond science. Extending this capability to visualize multi-electron correlation dynamics—capturing the temporal evolution of interactions among multiple electrons—remains an elusive goal. Understanding how many-body correlations and decoherence influence emergent phenomena is equally challenging, yet addressing these challenges could lead to fascinating quantum effects, with implications ranging from entanglement electronics to exploring the fundamental properties of quantum phases.

For QISE advances, achieving a reliable readout via quantum transduction—which converts quantum information in solids to different modes—is essential. Current developments are promising but require significant improvements to minimize losses detrimental to quantum-information applications. This underscores the need for further exploration into LMHs, digital alloys, highly efficient high-harmonic generation sources, and sophisticated quantum transduction techniques.

Concluding Remarks

With their unique electronic properties and reconfigurability, LMs and their heterostructures offer numerous opportunities in energy efficient ICT, neuromorphic computing, intelligent sensing, and QISE. Future AI systems will greatly benefit from large-scale synaptic circuits based on LMHs. As one of the fastest-growing electricity consumers globally, ICT can markedly improve its energy efficiency through integrating LMH optoelectronics and silicon-photonics. By integrating sensing systems with synaptic circuits, it becomes possible to directly process sensed information with AI algorithms, substantially mitigating information transmission bottlenecks.

This ongoing integration promises reduced production costs through simpler designs, while delivering higher data rates at lower power consumption, critical for advancing 5G, 6G, ubiquitous sensor networks, and AI. The capability of LMs to transmit and receive multiple wavelengths provides a cost-effective solution to achieve necessary data rates beyond the year 2025. Additionally, LMs used as broadband photodetectors (PDs) are pivotal for mid-infrared detection—the fingerprint region for many gases and molecules—where conventional silicon-photonics PDs are unsuitable. This is crucial for a range of applications in healthcare, security, and environmental monitoring.

For QISE, lightwave electronics presents unique opportunities to control and measure the dynamics of electronic quantum states and their correlations at natural time and length scales. The integration of LMs is essential in enhancing existing optoelectronics with entanglement processing capabilities. This could revolutionize classical technologies by increasing clock rates into the PHz regime, and quantum technologies by unlocking the full quantum potential of semiconducting LMs.

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