Electron-Wave-Stimulated Mid-Infrared Emission from Graphene-Substrate Quantum Oscillators

Byung Hee Hong[1,3]

Sunhwa Hong[1,3]‡, Moo Jin Kwak[2]‡, Yunseok Lee[3], Chan-Jin Kim[1,3], Sung Jin Hong[3], Ha Eun Lee[1,3], Yejun Lee[1], Koeun Kim[1], Juhyen Lee[2], Minkyung Lee[2], Youngdeog Koh[2], Joonhyun Lee[2], Miyoung Kim[3], Zee Hwan Kim[1], Myung Jin Park[3*], Hoon Wee[2*]

[1]Department of Chemistry, Seoul National University, Seoul 440-746, Korea. [2]Samsung Research, Samsung Electronics, Seoul 06765, Republic of Korea. [3]Graphene Square Inc. & Graphene Research Center, Advanced Institute of Convergence Technology, Suwon 16229, Republic of Korea

byunghee@snu.ac.kr

Generating tunable, high-intensity mid-infrared (MIR) to terahertz (THz) radiation on-chip remains a formidable challenge due to the rigid spectral limits of conventional thermal emitters. While graphene has emerged as a promising platform for light-matter interaction, active control of its radiative properties has been largely confined to surface-limited phenomena. Here, we introduce a new MIR radiation platform where multi-layer chemical vapor deposition (CVD) graphene is integrated with modular substrate oscillators. A pivotal discovery is that the extended de Broglie wavelength of drift carriers—acting as electron waves—facilitates long-range, coherent coupling with vibrational dipoles deep within the substrate bulk. This transforms the substrate into a three-dimensional volume emission source, where complex spectra of characteristic molecular and lattice vibration energies are additively synthesized on demand. The exponential scaling of radiation intensity ($\log I \propto V$) appears when the electrons' drift velocity in graphene exceeds the sound velocity of the substrates, exhibiting definitive evidence of quantum stimulated amplification associated with Cerenkov electron-phonon instability. Our work redefines the passive dielectric substrate as an active, programmable component stimulated by electron waves, paving the way for next-generation system-on-a-chip MIR-THz photonics, biomedical sensing, and highly efficient mode-specific electrothermal applications.

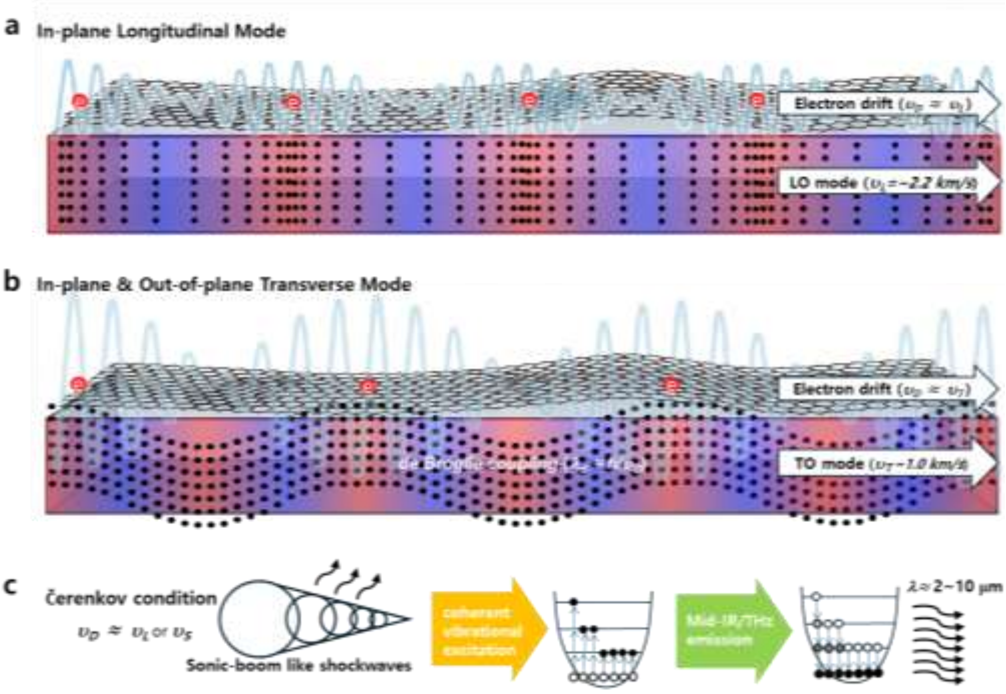

Figure 1: Origin of electron-phonon instabilities in graphene-substrate oscillators for MIR radiation. a and **b**, Schematics of Čerenkov electron-phonon instability between 3-layer graphene and a polymer substrate (polyimide) with respect to longitudinal and transverse sound waves (υ_L and υ_T), respectively. **c,** Schematic of Čerenkov condition that sonic boom like shockwaves coherently excite molecular or lattice vibrational modes of the substrates, followed by characteristic MIR emissions.