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Velocity Saturation of Hot Carriers in Two-Dimensional Transistors[1]

JONATHAN BIRD, University at Buffalo

Two-dimensional (2D) materials, including graphene and transition-metal dichalcogenides, have emerged in recent years as possible "channel-replacement" materials for use in future generations of post-CMOS devices. Realizing the full potential of these materials requires strategies to maximize their current-carrying capacity, while minimizing Joule losses to its environment. A major source of dissipation for hot carriers in any semiconductor is spontaneous optical-phonon emission, resulting in saturation of the drift velocity. In this presentation, I discuss the results of studies of velocity saturation in both graphene and molybdenum-disulphide transistors, emphasizing how this phenomenon impacts resulting transistor operation. While in graphene the large intrinsic optical-phonon energies promise high saturation velocities, experiments to date have revealed a significant degradation of the drift velocity that arises from the loss of energy from hot carriers to the underlying substrate. I discuss here how this problem can be overcome by implementing a strategy of nanosecond electrical pulsing [H. Ramamoorthy et al., Nano Lett., under review], as a means to drive graphene's hot carriers much faster than substrate heating can occur. In this way we achieve saturation velocities that approach the Fermi velocity near the Dirac point, and which exceed those reported for suspended graphene and for devices fabricated on boron nitride substrates. Corresponding current densities reach those found in carbon nanotubes, and in graphene-on-diamond transistors. In this sense we are able to "free" graphene from the influence of its substrate, revealing a pathway to achieve the superior electrical performance promised by this material. Velocity saturation is also found to be important for the operation of monolayer molybdenum-disulphide transistors, where it limits the drain current observed in saturation [G. He et al., Nano Lett. **15**, 5052 (2015)]. The implications of these results for 2D transistor performance will be explored in my presentation.

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