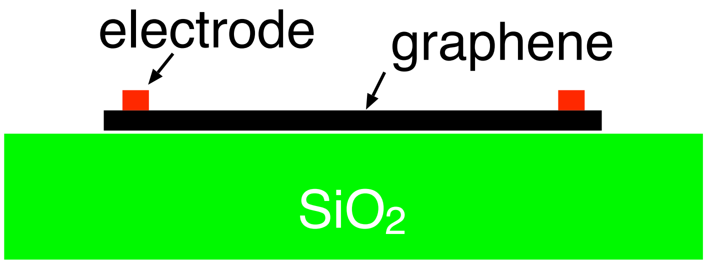
QUANTUM FRICTION AND GRAPHENE

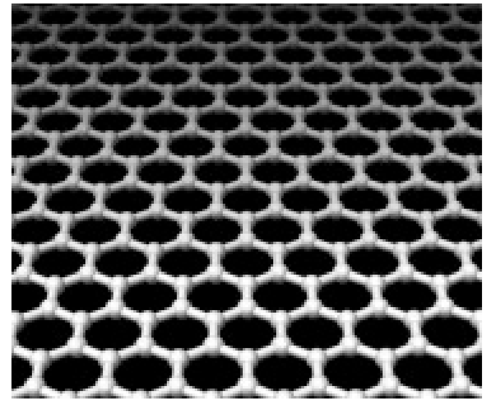
Aleksandr Volokitin

Research Center Jülich and Samara State Technical University

- Introduction
- Fluctuations produce forces
- Reflection produces friction
- Quantum friction between graphene and SiO_2
- Friction induces electric field
- Friction generates heat transfer
- Conclusion

Quantum friction





PRL **106,** 094502 (2011) PHYSICAL REVIEW LETTERS week ending 4 MARCH 2011

Quantum Friction

A. I. Volokitin[1,2,*] and B. N. J. Persson[1]

[1]*Institut für Festkörperforschung, Forschungszentrum Jülich, D-52425, Germany*

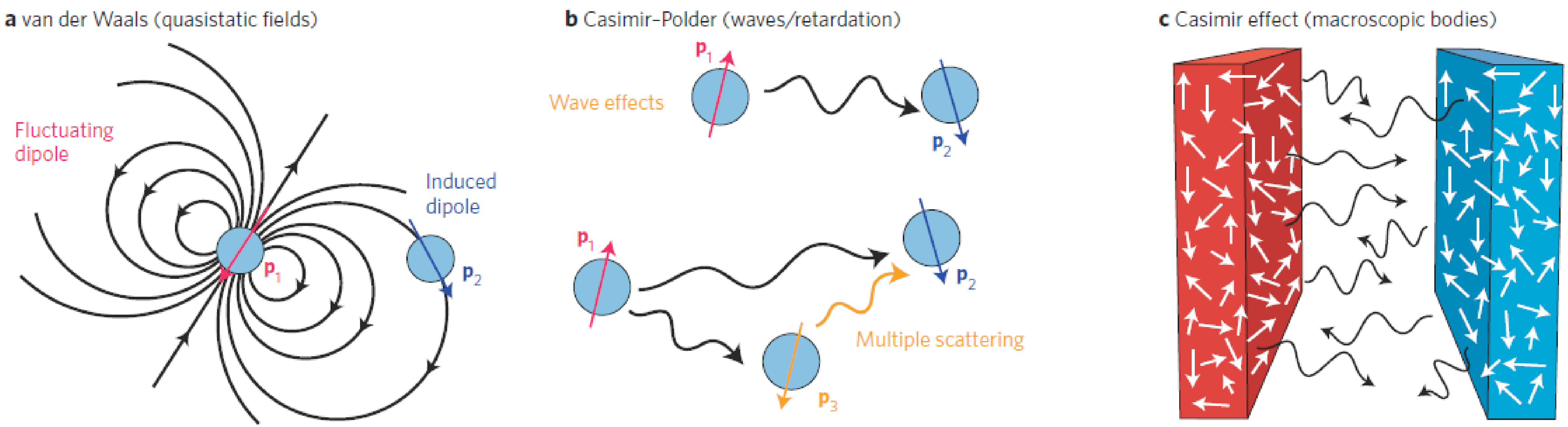
[2]*Samara State Technical University, 443100 Samara, Russia*

(Received 7 January 2011; published 2 March 2011)

We investigate the van der Waals friction between graphene and an amorphous SiO_2 substrate. We find that due to this friction the electric current is saturated at a high electric field, in agreement with experiment. The saturation current depends weakly on the temperature, which we attribute to the quantum friction between the graphene carriers and the substrate optical phonons. We calculate also the frictional drag between two graphene sheets caused by van der Waals friction, and find that this drag can induce a voltage high enough to be easily measured experimentally.

DOI: 10.1103/PhysRevLett.106.094502 PACS numbers: 68.35.Af, 44.40.+a, 47.61.−k

Fluctuations produce forces



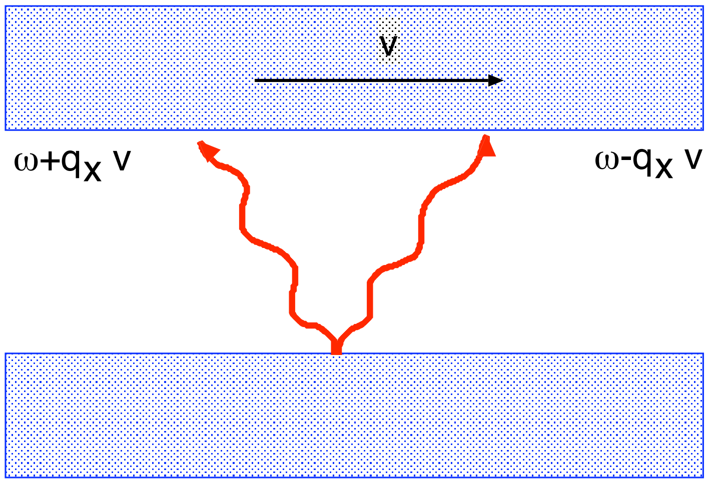
H.Casimir 1948

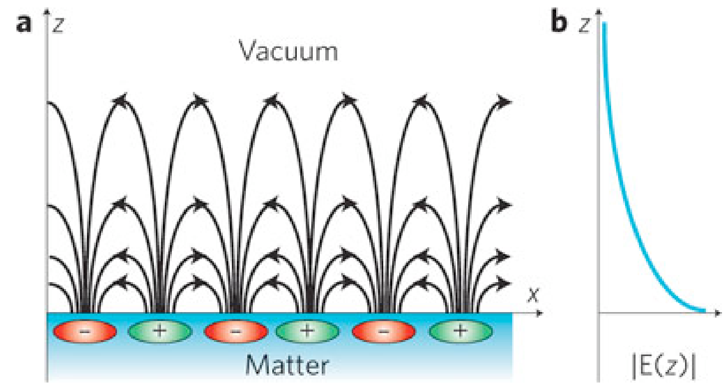
E.Lifshitz 1954

Quantum fluctuations dominate for $d < \lambda_T = c\hbar/k_B T$

Thermal fluctuations dominate for $d > \lambda_T = c\hbar/k_B T$

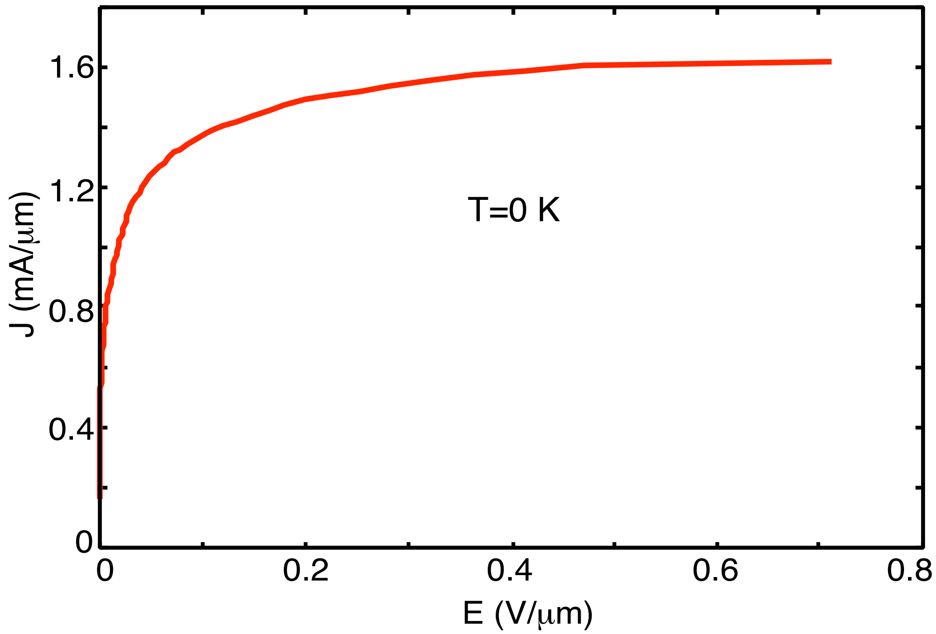
Reflection produces friction

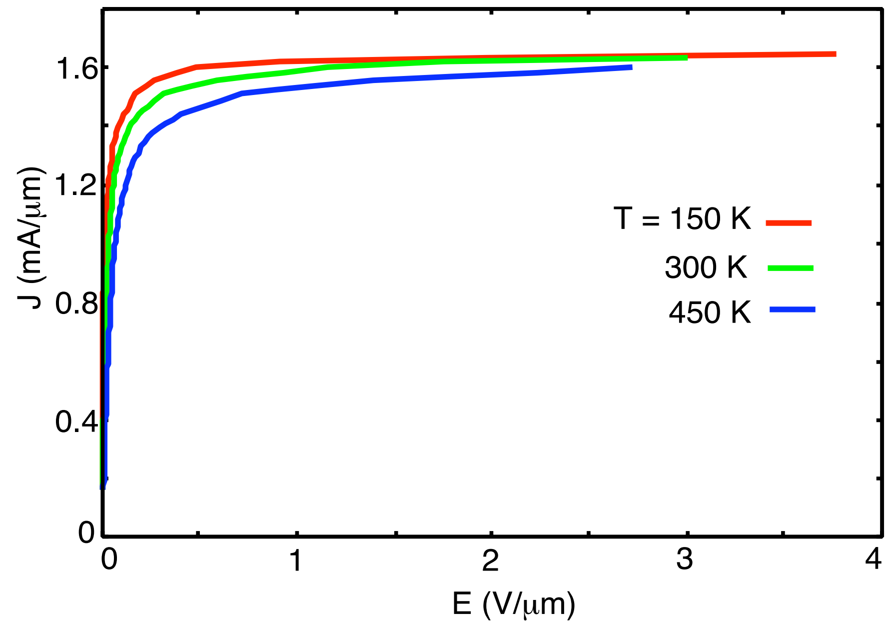




J.Pendry 1997
A.Volokitin and B.Persson 1998,2008
Doppler effect $\omega' = \omega - q_x v$
Thermal fluctuations dominate at $v < v_T = k_B T d/\hbar$
Quantum fluctuations dominate at $v > v_T = k_B T d/\hbar$

Current density-electric field dependence in graphene on SiO_2





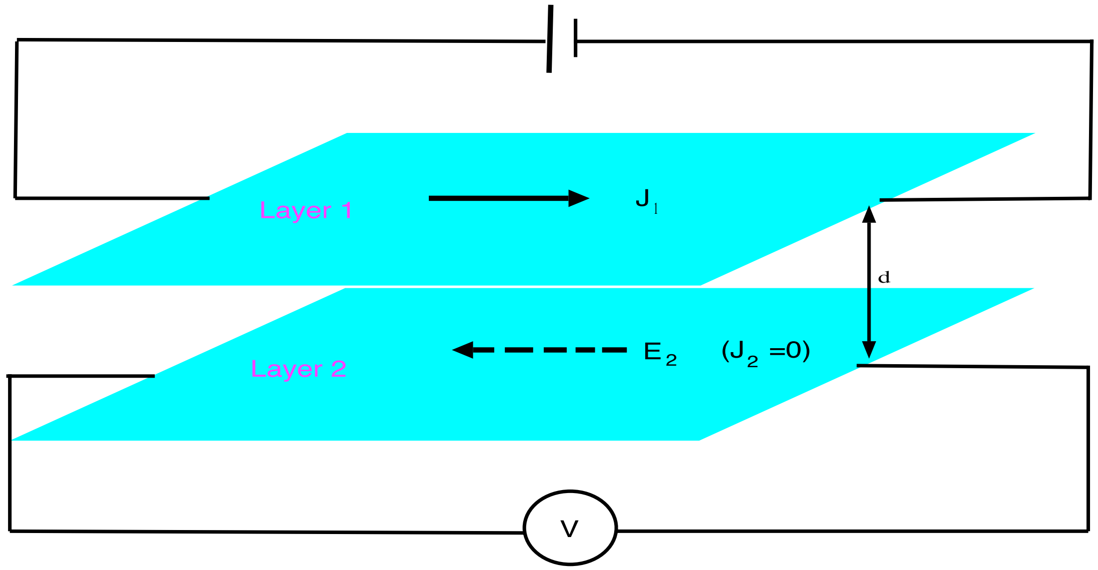
$n_s = 10^{12}\ cm^{-2}$

$$F_x(T_d, T_g, v)v = S_z(T_d, T_g, v) + \alpha_{phon}(T_g - T_d)$$

$$v_{sat} \sim \omega_{ph}/k_F \sim 10^6 m/s$$

$$J_{sat} = e n_s v_{sat} \sim 1\, mA/\mu m$$

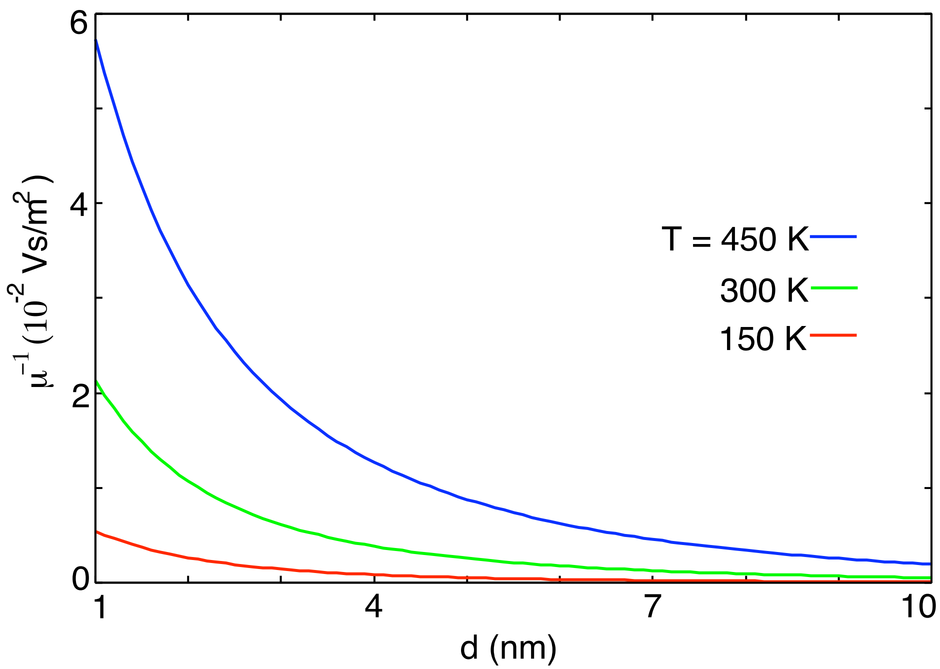
Friction induces an electric field



Theory. M. B. Pogrebenskii 1977, P. J. Price 1983
Experiment. T. J. Gramila *et.al* 1991, U. Sivan *et.al* 1992

Frictional Drag between Graphene Sheets

Low Velocities

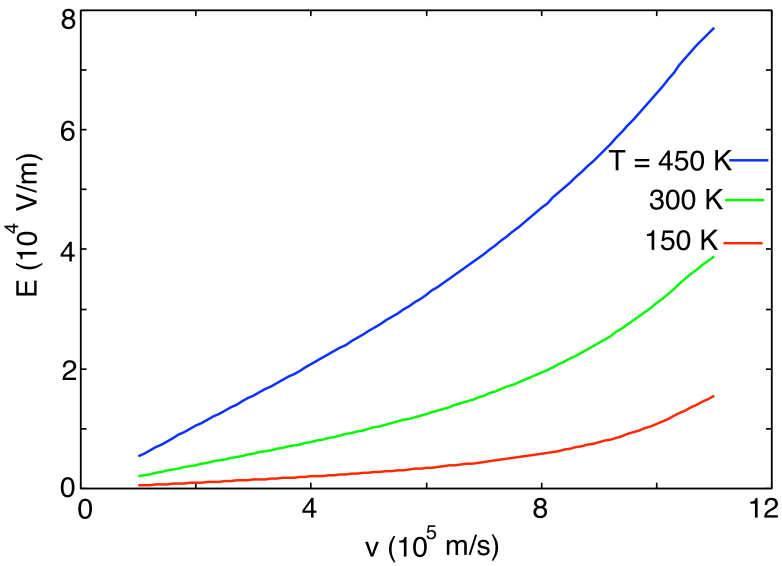


$n=10^{12}cm^{-2}$

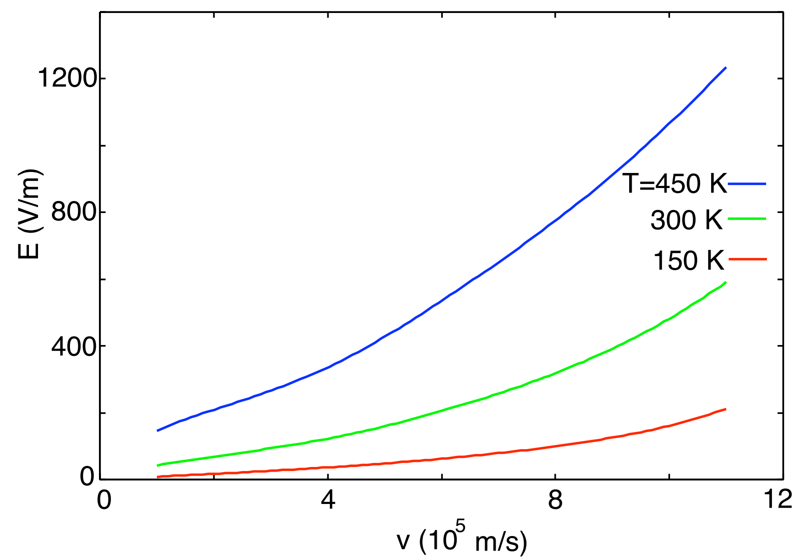
At low velocities $v \ll v_F$ induced electric field $E = \mu^{-1} v$.

Frictional Drag between Graphene Sheets

High Velocities

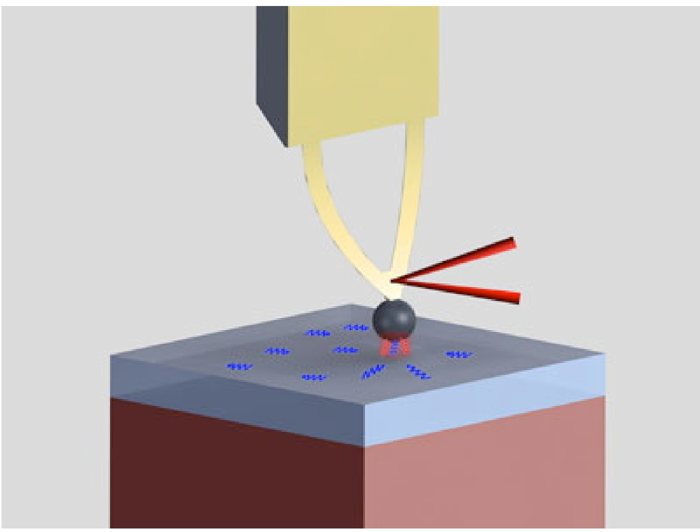


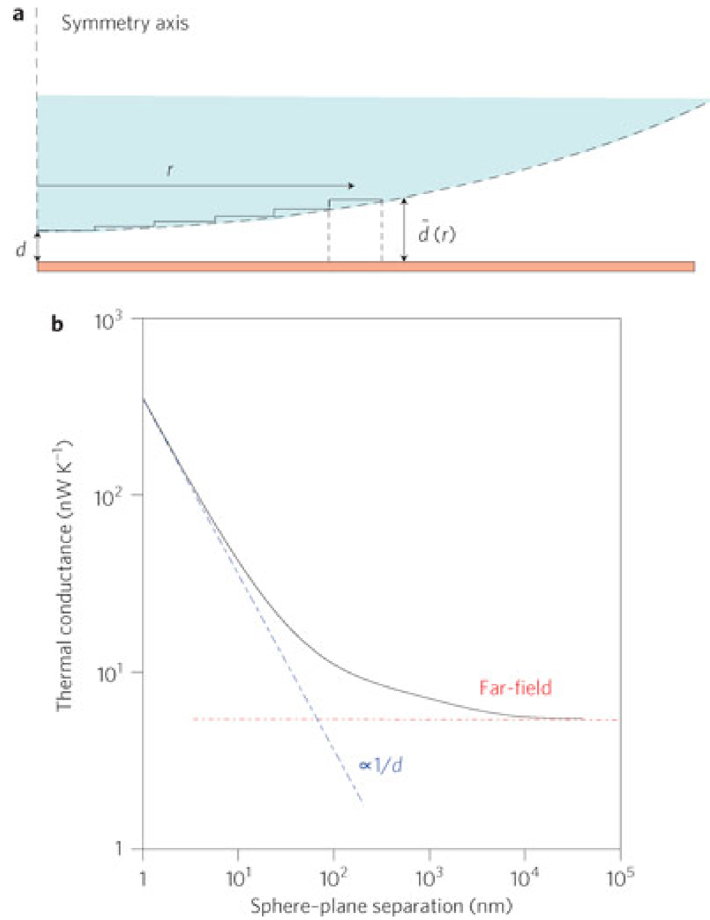
d=1 nm



d=10 nm

Radiative Heat Transfer.





Theory. D.Polder and M. Van Hove 1971
Experiment. Rousseau E. *et al* 2009; Shen S. *et al* 2009

Friction generates Heat Transfer

RAPID COMMUNICATIONS

PHYSICAL REVIEW B **83**, 241407(R) (2011)

Near-field radiative heat transfer between closely spaced graphene and amorphous SiO_2

A. I. Volokitin[1,2,*] and B. N. J. Persson[1]

[1] *Peter Grünberg Institut, Forschungszentrum Jülich, D-52425, Germany*

[2] *Samara State Technical University, 443100 Samara, Russia*

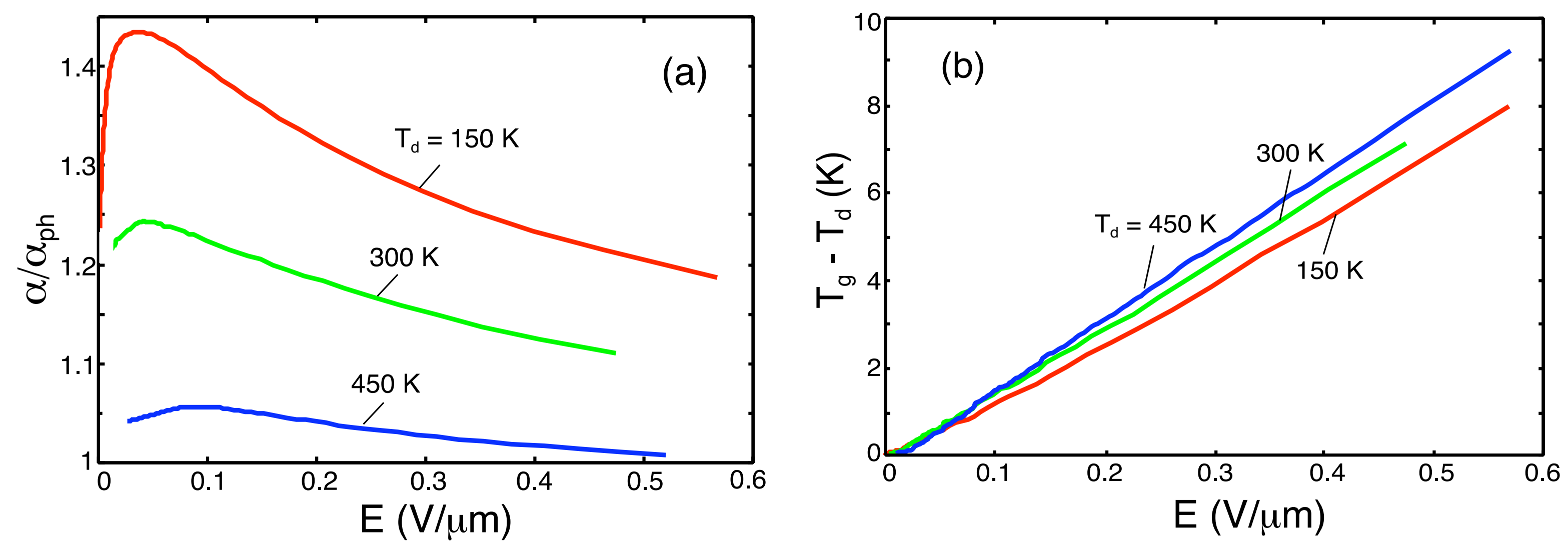
(Received 10 February 2011; published 27 June 2011)

We study the near-field radiative energy transfer between graphene and an amorphous SiO_2 substrate. In comparison with the existing theories of near-field radiative heat transfer our theory takes into account that the free carriers in graphene are moving relative to the substrate with a drift velocity v. In this case the heat flux is determined by both thermal and quantum fluctuations. We find that quantum fluctuations give an important contribution to the radiative energy transfer for low temperatures and high electric field (large drift velocities). For nonsuspended graphene the near-field radiative energy transfer gives a significant contribution to the heat transfer in addition to the contribution from phononic coupling. For suspended graphene (large separation) the corresponding radiative energy transfer coefficient at a nanoscale gap is ∼3 orders of magnitude larger than radiative heat transfer coefficient of the blackbody radiation limit.

DOI: 10.1103/PhysRevB.83.241407 PACS number(s): 73.23.−b, 44.40.+a

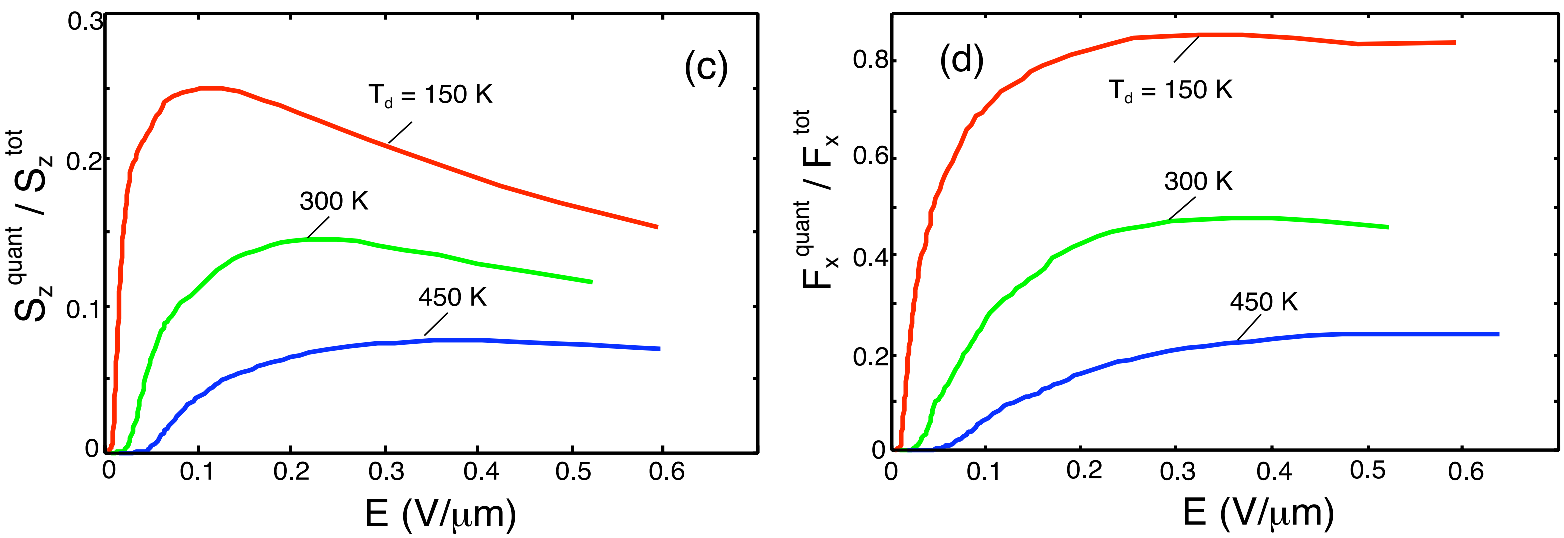
$$F_x(T_d, T_g, v)v = S_z(T_d, T_g, v) + \alpha_{phon}(T_g - T_d)$$

Phononic and Radiative Heat Transfer



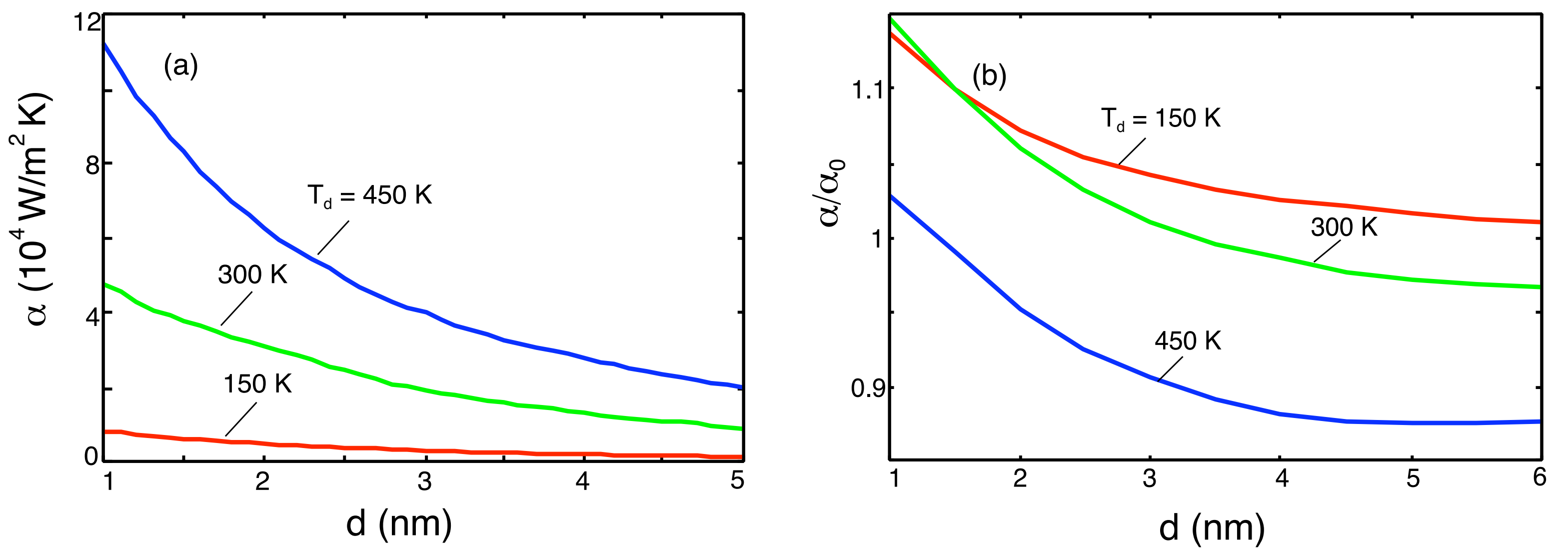
$$n = 10^{16}\, m^{-2},\; d = 0.35\, nm,\; \alpha_{ph} = 1.0 \times 10^{8}\, W\, m^{-2}\, K^{-1}$$

Quantum and Thermal Energy Transfer



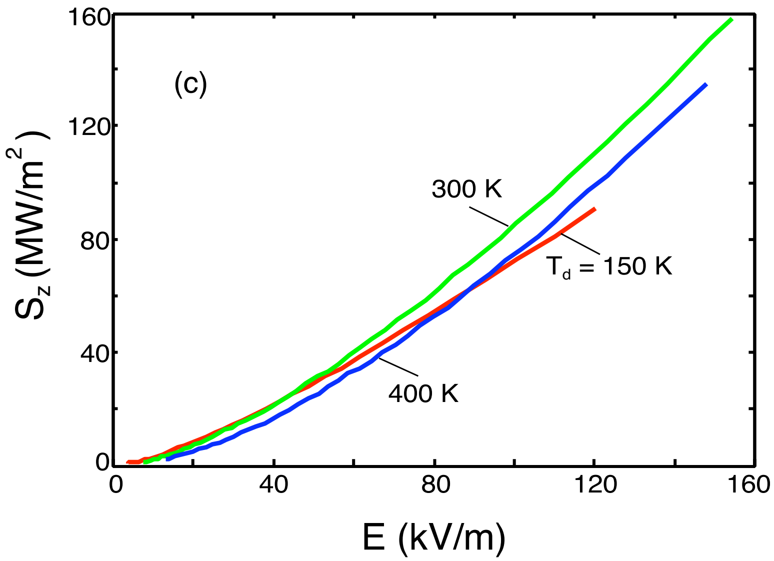
$$n = 10^{16}\, m^{-2},\, d = 0.35\, nm$$

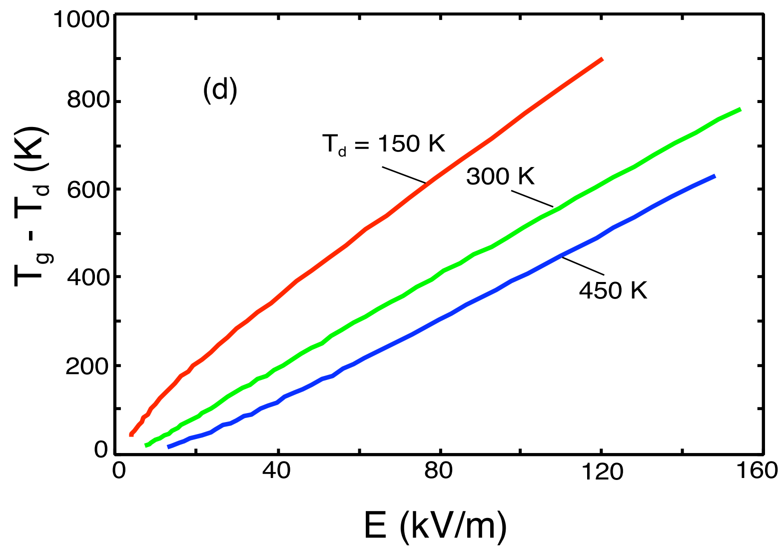
Radiative Energy Transfer



$$\frac{\alpha}{\alpha_0} = \frac{F_{fr}(T,v)v}{F_{fr}(T,V)v - S_z(T,v)}$$

Dependence of Heat Flux on Electric Field





$$d = 1\,nm$$

Conclusion

- Quantum friction has fundamental significance because, as superconductivity and superfluidity, it is manifestation of quantum laws on the macroscopic scale
- Quantum friction can has practical application in MEMS and NEMS and can be important in ultrasensitive force registration
- At present quantum friction can be studied using graphene field-effect transistor
- Quantum fluctuations can generates radiative energy transfer comparable with radiative heat transfer due to thermal fluctuations