A novel mesoscopic phenomenon: An analog of the Braess paradox in 2DEG networks

H. Sellier [1], **M. Pala** [2], **S. Baltazar** [2], **P. Liu** [1], **B. Hackens** [3], **F. Martins** [3], **X. Wallart** [4], **L. Desplanque** [4], **V. Bayot** [1,3], **and S. Huant** [1]

[1] *Institut Néel, CNRS & Université Joseph Fourier, BP 166, F-38042 Grenoble*
[2] *IMEP-LAHC, Grenoble INP, Minatec, BP 257, F-38016 Grenoble*
[3] *IMCN/NAPS, UCLouvain, 2 chemin du cyclotron, B-1348 Louvain-la-Neuve*
[4] *IEMN, UMR CNRS 8520, UST Lille, BP 60069, F-59652 Villeneuve d'Ascq*

Aharonov-Bohm oscillations and universal conductance fluctuations are emblematic interference effects in mesoscopic nanostructures of two-dimensional electron gas (2DEG). While studying quantum networks with asymmetric parallel channels, we discovered a new phenomenon which is a mesoscopic analog of the classical Braess paradox [1]. This counter-intuitive effect was first described for congested road networks where adding a new road can paradoxically lead to a deterioration of the overall traffic situation. Known so far in classical situations only, including electrical and mechanical networks, we have extended the concept of the Braess paradox to mesoscopic semiconductor networks where electron transport is governed by quantum mechanics [2].

Our network has three branches connected asymmetrically with respect to source and drain contacts as shown in the figure. The vertical wires are narrower than the horizontal ones to behave as congested channels. Numerical simulations of quantum transport through this network show that the presence of the central wire decreases the overall conductance although intuition tells us that it should increase the conductance by adding extra channels. Remarkably, this phenomenon is robust with respect to Fermi level variations and cannot be reduced to previously known mesoscopic effects in nanostructures.

Then, we have considered scanning gate microscopy [3] as a versatile tool to control the transmission of the central channel with the sharp tip of a cryogenic AFM microscope that induces a local potential change in the 2DEG. Numerical simulations of the network transmission as a function of the tip position show that the transmitted current is increased, instead of decreased, when the tip is placed above the central channel with a negative voltage that depletes locally the 2DEG (see figure). This network has been fabricated in a high-mobility GaInAs/AlInAs heterostructure with dimensions that ensure ballistic and coherent transport at low temperature. Using a scanning gate microscope at 4.2 K, we have observed such a counter-intuitive Braess-like effect that can be distinguished from other mesoscopic effects. This mesoscopic analog of the classical Braess paradox raises fundamental questions that will be discussed and may find applications in future quantum devices.

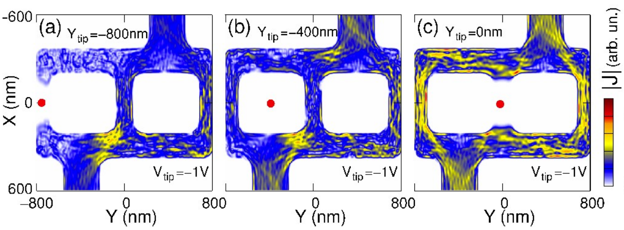

Figure : Color plots of the current density for three tip positions indicated by the red dots.

[1] D. Braess, Unternehmensforschung **12**, 258 (1968).
[2] M. Pala *et al.*, Phys. Rev. Lett. **108**, 076802 (2012); Nanoscale Res. Lett. **7**, 472 (2012).
[3] B. Hackens *et al.*, Nat. Phys. **2**, 826 (2006).