Mottronics: towards a novel electronic based on Mott insulators

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After half a century of miniaturization, microelectronics is facing two major issues related to the downscaling limit and the energy consumption. To overcome these challenges, exploration of new strategies includes the search for new materials, new physics and new architectures.

In this context, quantum materials have attracted much attention. In particular, Mott insulators standing as a broad class of quantum materials are expected to be metallic according to conventional band theory, but are insulating due to on-site electron-electron repulsions. In such systems, electronic doping or external pressure may drive insulator to metal transitions (IMT) and lead to remarkable properties such as high Tc superconductivity or giant magnetoresistance.

During the last decades, filling or bandwidth control IMT in Mott insulators (i.e. the Mott transition) have been the subject of intense fundamental researches [1]. However, the use of these IMT in applications remains quite scarce for a very simple reason. Indeed, pressure or doping are not easily controllable parameters in real devices. Our group at IMN demonstrated that the electric field is an efficient parameter to destabilize the Mott insulating state and induce an insulator to metal transition [2]. We first evidenced the non-volatile and reversible switching on single crystals and further validated it on polycrystalline thin layers for several members of the Mott Insulator family [3].

This phenomenon, coined as "Electric Mott Transition" (EMT), is promising for microelectronic applications and could open the door to a novel electronics based on Mott insulators, called Mottronics [4]. Further studies highlighted that this EMT is induced by the massive creation of hot electrons leading to an electronic avalanche within a filamentary conductive path [5]. We demonstrated that this mechanism is driving EMT's in many Mott insulators with different chemical compositions, such as the chalcogenides AM_4Q_8 (A=Ga,Ge; M=Nb,V,Ta,Mo; Q=S,Se,Te) and $Ni(S,Se)_2$, the oxides $(V_{1-x}Cr_x)_2O_3$ and the molecular system $Au(Et\text{-}thiazdt)_2$ [6].

The characteristics of the non-volatile EMT are suitable for information storage: ''Mott memories'' display significant advantages compared to ReRAM based on metal oxides (OxRAM) or phase change materials (PCRAM) [7]. Furthermore, we have shown that a Mott insulator, subjected to a train of electric pulses, may display a Leaky-Integrate-and-Fire behavior based on the volatile EMT. Mott insulators therefore reproduce the main functionalities of neurons in human brain that make them potentially suitable to build up artificial neurons and hardware artificial neural networks [8]. An interesting disruptive solution would be indeed to replace the energy-intensive software networks with energy-efficient "hardware" networks of artificial neurons and synapses, i.e. building blocks based on Mott insulators.

In the longer term, our recent works based on the use of ultrafast lasers shows that ultimate switching times in the picosecond range are achievable in electro-optical or all-optical devices based on Mott insulators [9].

This presentation will first review the electric Mott transition and the new functionalities enabled by this property. It will then present some examples of Mottronics devices in particular for data storage and artificial intelligence applications.

[1] D. B. McWhan and J. P. Remeika, Phys. Rev. B, **2**, 3734 (1970); A. Georges *et al.*, Rev. Mod. Phys. **68**, 13 (1996); A. Milloch *et al.*, arXiv:2409.04154.

[2] L. Cario *et al.*, Adv. Mater., **22**, 5193, (2010) ; E. Janod *et al.*, Adv. Funct. Mater. **25**, 6287, (2015).

[3] E. Souchier *et al. Phys. Stat. solidi-RRL* **5**, 53 (2011); J. Tranchant *et al.* Thin Solid Films 533, 61 (2013); M. Querré *et al.*, Thin Film Solids **617**, 56 (2016); M. Rodriguez-Fano *et al.,* ACS Appl. Mat. & Interfaces, **15**, 54611, (2023).

[4] Y. Tokura *et al.*, Nature Physics 13, 11 (2017).

[5] V. Guiot *et al.*, Nature Commun. **4**, 1722 (2013).

[6] P. Diener *et al.*, Phys. Rev. Lett. **121**, 016601 (2018); P. Stoliar *et al.*, Advanced Mater. **25**, 3222 (2013).

[7] L. Laborie *et al.*, 52th IEEE SISC San Diego (CA) (2021); J. Tranchant *et al.*, IEEE IMW, 1-4 (2018).

[8] P. Stoliar *et al.* Adv. Func. Mater. **27**, 1604740 (2017); C. Adda *et al*. J. Appl. Phys. **124**, 152124 (2018).

[9] D. Babich *et al.,* Phys. Rev. Applied **17**, 014040 (2022); T. Amano *et al.*, Nature Physics (2024), doi: 10.1038/s41567-024-02628-4.