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Evolutions of the Dirac Fermions in Monatomic Layers

LESS IS DIFFERENT.

Vapor deposition of three-dimensional (3-D) crystal on a substrate often results in formation of the novel 2-D materials with intriguing electronic states [1]. The approach has been well-known in the field of "Surface Science", which has attracted our attentions over the past decades. Triggered by fabrication of the graphene layers, researches on such monatomic sheets have extended to layers of van der Waals crystals and also to groups of Xene such as silicene, germanene and so on. A monatomic layer itself corresponds to the minimum unit of a matter and changes the functionalities depending on chemical compositions and structures. While a considerable number of monatomic layers has been reported on solid surfaces and in van der Waals crystals, novel layers have still been discovered today. Here, we present our recent works on novel monatomic layers that possess intriguing Dirac Fermions (Fig.1). The researches were made with soft X-ray spectroscopies, such as photoemission spectroscopy, that have been used to directly probe electronic states of monatomic layers and also to examine carrier dynamics under the *operando* condition.

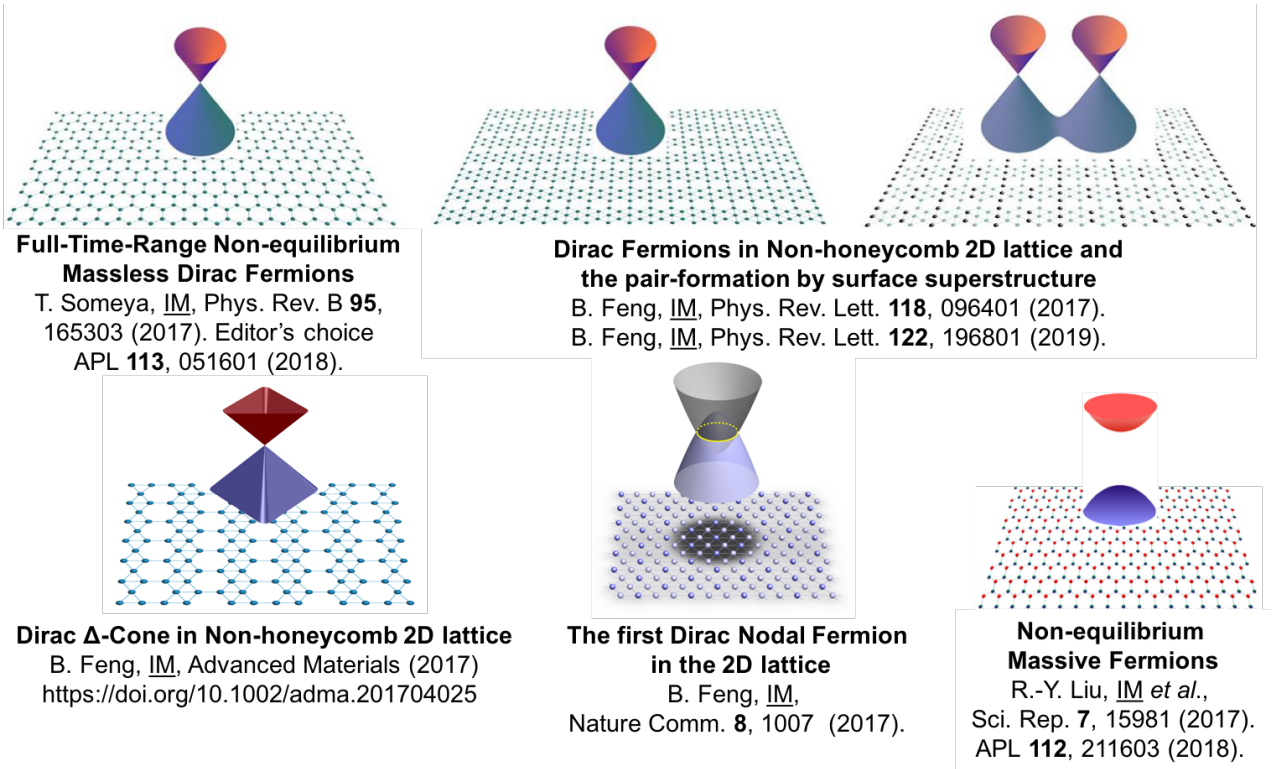

Figure 1 A gallery of Dirac bands, realized in various kinds of monatomic layers

We observed Dirac Fermions in a 2-D boron sheet, borophene, that forms spontaneously on the Ag(111) surface[2]. Furthermore, we found pairing of the Dirac cones due to Moire-periodic perturbations of the overlayer-substrate interactions [2]. The effect is found to explain the Dirac cone pairs, observed in a 2-D silicon sheet, silicene, on Ag(111)[3]. On the other hand, in the Cu_2Si monolayer, we discovered the 2-D Dirac nodal line fermions when it is prepared on the Cu(111) surface[4]. However, the layer becomes a simple 2-D metal on Si(111) [5]. These cases demonstrate evolutions of Dirac Fermions, Dirac cones and Dirac nodal lines, in monatomic layers by substrates. Such a substrate effect, thus, can be regarded as a new degree of freedom to regulate the Dirac bands.

Based on this concept, we have investigated a possible electronic control of a free-standing monatomic layer that has two surfaces and no bulk in between, the extreme case of surface science [6]. We made hydrogenation of a borophene layer that have Dirac nodal lines and synthesized a HB sheet (borophane) from a MgB_2 crystal [7]. Figure 2 shows a collection of layers of honeycomb borophene in different chemical environments. The HB sheet becomes semi-metallic with electron and hole pockets at different symmetry points. The electron band originates from the B-H-B bond, while the hole band is kept from one of the Dirac bands in MgB_2. The synthesis and 'extreme' surface modification of free-standing boron sheets offer the potential of designing and developing new boron-based devices.

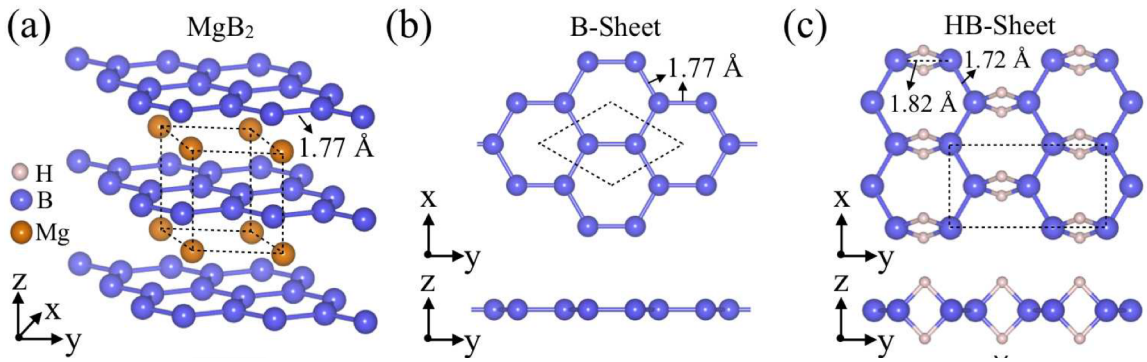

Figure 2 B-sheets (a) in a MgB_2 crystal, (b) in a free-standing manner, and (c) after hydrogenation (HB-sheet).

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