Observation of Fast Dirac Nodal-Line Fermions in a Nonsymmorphic Superconductor, $HfP_{1.55}Se_{0.45}$

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In recent years, incorporating superconductivity into the Dirac nodal-line semimetal (DNLS) is expected to provide a platform for exotic physical properties. Therefore, such candidates have been extensively explored. Despite extensive exploration of DNLS, only a few superconductors have been found among them to date. For instance, a DNLS, $PbTaSe_2$, exhibits Dirac velocity of 4×10^5 m/s and superconducting critical temperature (T_c) at 3.8 K [1]. Recently, a nodal loop has been observed in $ZrP_{2-x}Se_x$, which crystallizes in a nonsymmorphic space group (P4/nmm) and exhibits the superconductivity below T_c = 6.2 K [2]. Notably, it has been reported that $HfP_{2-x}Se_x$ also shows superconductivity below T_c = 5.5 K [3]. Replacing Zr (Atomic number, Z=40) with Hf (Z=72) leads to the shrinkage of lattice constants and the increase in spin-orbit coupling strength. Therefore, a substantial impact on the electronic structure is expected. In this study, we determined the electronic structure of $HfP_{1.55}Se_{0.45}$ by using synchrotron-radiation angle-resolved photoemission spectroscopy (ARPES) at BL-1 of Hiroshima Synchrotron Radiation Center, and investigated the Hf substitution effect by comparing $HfP_{1.55}Se_{0.45}$ with $ZrP_{1.24}Se_{0.57}$.

Figure 1(a) shows the Fermi-surface map of $HfP_{1.55}Se_{0.45}$. Two square-shaped Fermi surfaces enclosing M and Γ points, which are denoted by α and β, respectively, are observed. They are separated in wavenumber space by a nearly constant distance of 0.3 π/a, where a is an in-plane lattice constant. Figure 1(b) shows the band structures observed along the Γ-M line of $HfP_{1.55}Se_{0.45}$. Here we have found that two straight dispersions, which form α and β Fermi surfaces, intersect with each other at -0.9 eV and exhibit Dirac velocity of 1.3×10^6 m/s. We have also observed that the crossing point is continuously connected in wavenumber space and forms an in-plane closed nodal loop. These results provide evidence of the Dirac nodal-line fermions in $HfP_{1.55}Se_{0.45}$.

We can deduce the Hf substitution effect from the comparison between the results of $HfP_{1.55}Se_{0.45}$ and $ZrP_{1.24}Se_{0.57}$. The number and shapes of Fermi surfaces are similar between them. However, in the result of $HfP_{1.55}Se_{0.45}$, the energy of the crossing point is closer to the Fermi level and the distance between the α and β Fermi surfaces is narrower than $ZrP_{1.24}Se_{0.57}$. It should be noted that the Dirac velocity, 1.3×10^6 m/s, for $HfP_{1.55}Se_{0.45}$ is even higher than that, 1.2×10^6 m/s, for $ZrP_{1.24}Se_{0.57}$.

Our results indicate that the gapless Dirac nodal loop is robust against the change of lattice parameter and spin-orbit coupling strength by the replacement of Zr with Hf. The decrease in T_c upon replacing Zr with Hf may be related to the substantial difference in the low-energy electronic structure.

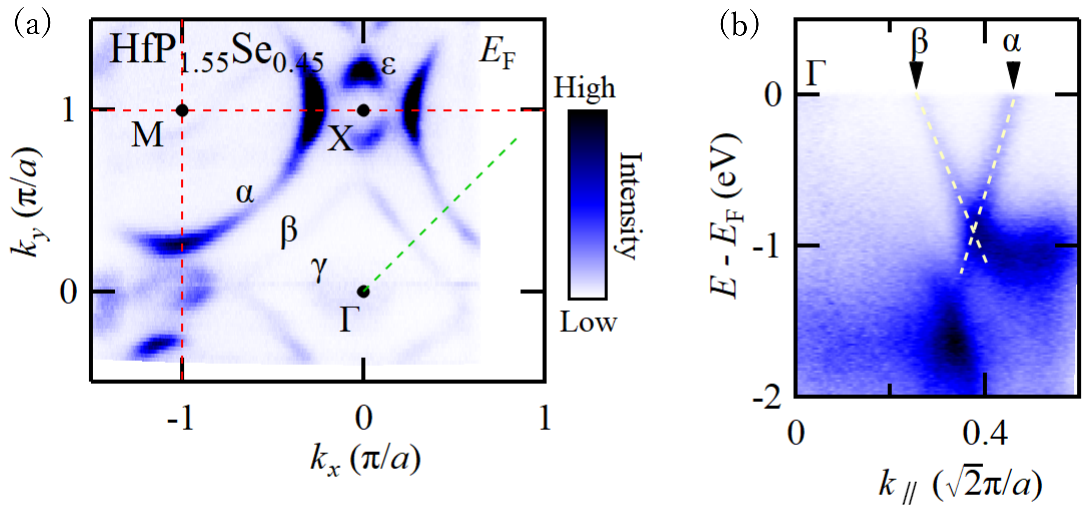

FIGURE 1. ARPES data of $HfP_{1.55}Se_{0.45}$, acquired with *hν* = 50 eV. (a) Fermi-surface map. (b) *E*-*k* plot along Γ - M line.

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