Decades ago, the discussion of planetary formation in solar system was developed for the solar system (Hayashi et al. 1985 ). Two representative formation scenarios for Jupiter have been proposed: Core accretion (Perri & Cameron 1974 ; Mizuno 1980 ; Pollack et al. 1996 ) and disk instability (Kuiper 1951 ; Boss 1997 ; Mayer et al. 2002 ). In theory, the two planetary-formation processes have different dependences on disk metallicity, which is defined as the ratio of the metal-number-density to hydrogen atoms, and planet mass (e.g., Matsuo et al. 2007 ). For the core accretion model, a proto-planet core easily grows to the critical core mass before the disk gas dissipates. This occurs because the disk metallicity reflects the building materials available for the core (Ida & Lin 2004b ; Mordasini et al. 2012 ). In fact, since the first planet orbiting a normal star was discovered (Mayor & Queloz 1995), large-sized radial velocity observations have revealed that, while the metallicities of stars hosting smaller planets such as Neptune-like planets and super-Earths are significantly lower than those of stars orbited by extrasolar gas giants (Mayor et al. 2011; Wang & Fischer 2015), the gas giants preferentially orbit metal-rich stars (e.g., Santos et al. 2003; Fischer & Valenti 2005). Because the central star and its surrounding protoplanetary disks are formed from a same molecular cloud, according to the primordial hypothesis, most gas giants are thought to have formed via the core accretion. Regarding the planet mass, the gas giants with planet mass up to 30 MJ are potentially formed via the core accretion (e.g., Tanigawa et al. 2008; Tanigawa & Tanaka 2016). The number of the gas giants also decreases as the planet mass is higher (e.g., Mordasini et al. 2009). For the disk instability scenario, --induced planetary formationnegative Although the lower limit on the masses of the disk-instability-induced planets may exist (Matsuo et al. 2007), the mass distribution of the gas giants formed via the disk instability still remains an open question. On the other hand, direct imaging of extrasolar planets orbiting HR8799, Formalhaut, and beta Pictoris reported in 2008 and 2010 (Marois et al. 2008; Kalas et al. 2008; Lagrange et al. 2010), respectively, confirmed the existing of outer planets, which can be naturally explained by the disk instability scenario rather than the extended core accretion with migration or planet-planet scattering (Dodson-Robinson et al. 2009). Thus, there may exist two populations originated from the two planetary formations.

Several previous studies showed that the gas giants are divided into two regimes with a boundary mass of 4 MJ and interpreted the two populations as an outcome originated from the two planetary formations (Ribas & Miralda-Escude 2007; Santos et al. 2017; Schlaufman 2018); while the gas giants lighter than 4 MJ are core-accreted planets, the gas giants more massive than 4 MJ may be formed through disk instability. However, it is possible to form very massive gas giants up to 30 MJ via the core accretion in theory (e.g., Tanigawa et al. 2008; Mordasini et al. 2009; Tanigawa & Tanaka 2016) and the upper mass limit of the core-accreted planets is also expected to depend on the disk metallicity (Mordasini et al. 2012). Pebble accretion has been recently proposed as the third planetary formation scenario that enables massive core to be formed in the outer region beyond 10AU (Ormel & Klahr 2010; Lambrechts & Johansen 2012); more massive planets than the core-accreted planets are potentially formed thanks to wider hill radius. Thus, whether the boundary mass of 4 MJ can be applied as the upper boundaries of the bottom-up planetary formation scenarios such as the core accretion and pebble accretion is still unknown. Furthermore, although the previous studies did not consider the selection effects of the planet detections, the detection limits of the radial velocity measurements clearly depend on the metallicity of the host star (see Figure 1a).

In this paper, we re-investigate what the upper-mass limits of the bottom-up planetary formation scenarios are and explore the possibilities of multiple populations in the extrasolar planetary systems discovered to data through evaluating the distributions of the planet masses and eccentricities in the metal-rich and -poor regions, minimizing the measurement biases for the host-star metallicity and stellar mass, which are not derived by using the uniform method (e.g., Santos et al. 2004; Sousa et al. 2008), and the detection biases of the radial velocity measurements. This paper is organized as follows. In Section 2, we explain how the samples gathered for this study were composed and how the distributions of the planet masses, eccentricites, and semi-major axes in the metal-rich and -poor regions were evaluated. In Section 3, we derive the boundary metallicity that is divided into two regions such that the distributions of the planet masses and semi-major axes are most different and investigate how the samples are divided with the Gaussian Mixture Model (GMM). In Section 4, we discuss what the upper-mass limit of the gas giants formed via the bottom-up planetary formation is and whether the disk-instability-induced planetary formation occurs.