Characterization of non-radiative Bloch modes in a plasmonic triangular lattice by electron energy-loss spectroscopy

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Control of surface plasmon polaritons (SPPs), which are collective oscillations of free electrons excited at the metal/dielectric interface, is important for localizing light energy near the surface. In a metal surface with periodic structures, so-called plasmonic crystals (PlCs), SPPs behave as Bloch waves due to Bragg diffraction and energy gaps open where dispersion curves cross each other. SPP propagation and confinement can be effectively controlled on PlCs, so PlCs are expected to be applied to next-generation optical devices[1]. Among a variety of PlC structures, a plasmonic triangular lattice (Tri-PlC) is promising because its first band gap can be a full gap where SPPs are not allowed to propagate in any directions[2]. In the previous study, spatial and momentum resolved cathdoluminescence (CL) experiments have completely revealed Bloch modes around the second bandgap of Tri-PlCs[3], but detectable modes by CL technique are intrinsically limited inside the light line where Bloch modes can be coupled with light. Characterization of Bloch modes around the first bandgap requires electron energy-loss spectroscopy (EELS) because the first bandgap opens outside the light line where any Bloch modes are non-radiative.

In this study, a Tri-PlC film with a period of 600 nm was prepared by a replica method (Fig. 1a). This Tri-PlC film was an Al disk array with a height of 90 nm placed on the Al film with 100 nm thick. Under the empty lattice approximation (ELA), the M point is at 1.19 eV and the K point is at 1.37 eV (Fig. 1b and 1c), and the first bandgap is expected to be formed near those energy levels. The Bloch modes around the first bandgap were characterized by EELS combined with scanning transmission electron microscopy (STEM). The obtained EELS spectra include a large amount of volume losses since the direction of the electron beam was the surface normal of the Tri-PlC film. So we defined the change rate as $\{I_{Tri\text{-}PlC}(E)-I_{flat}(E)\}/I_{flat}(E)$ to emphasize the signals of Bloch modes, where $I_{Tri\text{-}PlC}(E)$ and $I_{flat}(E)$ are the spectral intensities taken from the Tri-PlC and the flat Al specimen with 100 nm thick, respectively.

A part of results is shown in Fig. 1d, where two change rates are compared. One was extracted from the lattice points (centers of the Al disks) and the other one was extracted from the inter-lattice points (flat areas outside the Al disks). In the change rate of the lattice points, a peak appears lower than 1.19 eV (M point under the ELA), indicating that the Bloch modes below the first bandgap are localized at the lattice points. The change rates of the lattice points and the inter-lattice points are crossing each other at 1.26 eV, and above this energy level, the change rate of the inter-lattice points is higher than that of the lattice points. This fact indicates that the Bloch modes above the first bandgap distribute outside the Al disks. We also obtained the change rate maps, and they were compared with theoretical models based on the group theory.

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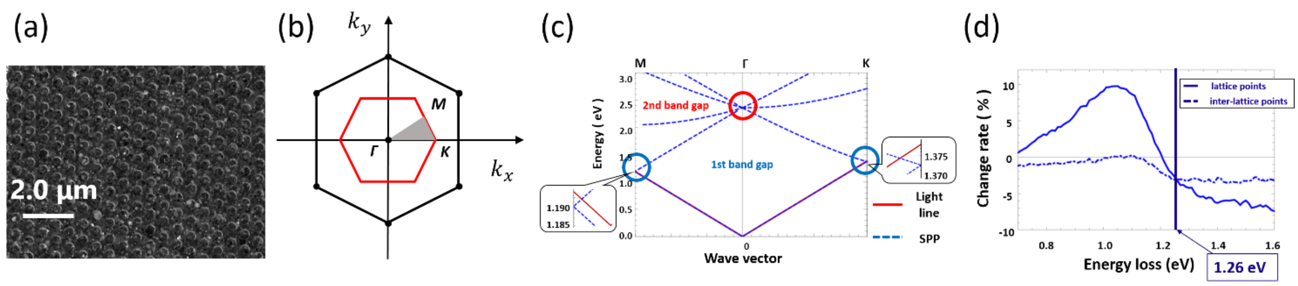

Fig. 1 (a) A STEM image of the Tri-PlC film, (b) a reciprocal lattice of the triangular lattice, (c) the plasmonic band structure of the Tri-PlC under the empty lattice approximation, (d) Change rates extracted from the lattice points and the inter-lattice points.