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In situ size dynamics and manipulation of nanoparticle interaction under electron beam irradiation

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Background

The size-dependent properties of gold (Au) nanoparticles (NPs) have unique applications in various fields including science and technology ranging from environmental sensing and catalysis to drug delivery and biomedical imaging due to their excellent catalytic, electronic and optical properties. The practical applications of AuNPs in all fields usually require external stimuli, such as electron beam irradiation, temperature variations and mechanical compressions, which provide a further understanding of dynamics including the influence of kinetics of nanoparticle transformations and thermodynamic stability. However, such external stimuli induce structural transformations in AuNPs depending upon their intensity. In recent years, several studies have been conducted to understand the dynamic behavior of AuNPs under the control conditions to exploit their full potential and broaden their applicability in diverse fields. For this purpose, the comprehensive use of transmission electron microscopy (TEM) has already been implemented to study real-time in situ dynamic changes in NPs. The most common coalescence phenomenon is well documented in the literature, nonetheless, the nanoparticle size dynamic and repulsion phenomenon are considered here as a background for the knowledge gap.

The use of high-intensity electron beam irradiation in TEM outcomes in a beam-induced phase transition, surface charging, ionization and defects, providing insights to observe structural changes in individual metal NPs and interactions between a pair of coupled metal NPs at the nanoscale [1,2]. This study aims to investigate the dynamic behavior of AuNPs under the influence of electron beam irradiation including the interaction between closely placed a pair of AuNPs resulting in coalescence or repulsive behavior between them. The study made use of different surface substrates, such as carbon and silicon nitride (SiN) to additionally explore the effect of substrate-nanoparticle interactions.

Furthermore, we target our focus on the interaction between different coupled NPs induced by surface charges, electrostatic forces, interparticle distance and size dynamics. By accomplishing these objectives, we aim to contribute to a deeper understanding of NPs manipulation for their applications in advanced photonic and plasmonic nanodevices.

Methods

Different-sized AuNPs on carbon and SiN substrates were irradiated under a controlled dose of an electron beam using TEM. In situ imaging was acquired using the OneView Gatan camera system to monitor dynamic changes in AuNPs.

Results

Several intriguing phenomena were observed upon the irradiation of the electron beam. Firstly, the individual spherical NPs showed remarkable structural transition, involving the structure transformation, for example, from face-centered cube (fcc) to a decahedral facet structure. The structural changes observed with atomic diffusion and structure reconstruction across the substrate are due to the transferred energy from the electron beam, during the electron-matter interactions. Furthermore, two more phenomena were observed in the case of coupled AuNPs, such as coalescence and repulsion between a pair of coupled AuNPs under an electron beam depending on the electron dose, interparticle distance and size dynamics. Coalescence is a favorable phenomenon which is initiated with the formation of a neck-like structure with the lattice reorientation between two NPs in order to transform to a more stable structure by minimizing the overall surface energy and generating more localized plasmon at the particle-particle interface [3,4]. On the other hand, the repulsion phenomenon is also affirmative under the electron beam interactions governed by surface charge dynamics and electrostatic forces on a carbon substrate, which play a pivotal role in stability and dispersion under electron beam irradiation.

Conclusions

This study provides valuable insights into nanodynamic behavior of AuNPs under the influence of electron beam interaction to explore different nanoscale phenomena on carbon and SiN substrates. The dynamic behavior of AuNPs showed the structural transformation, coalescence and repulsion phenomena on carbon substrate under the electron beam irradiation. Contrarily, strong adhesive interaction between AuNPs and SiN substrate restricted the NPs diffusion across the surface leading to the melting of NPs under electron beam irradiation due to the transferred energy, consequently confining the coalescence and repulsion phenomena. Whereas heating treatment favored the coalescence phenomenon on SiN substrate.

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Furthermore, the dynamic behavior of AuNPs was recorded as perturbation and rotation of NPs on both substrates under electron beam effects. These outcomes contribute to a deeper understanding of AuNPs size and surface dynamics to manipulate for various applications, such as in material science including nanodevices, and nanotechnology. Future research directions may consider the substrate-nanoparticle interaction in depth using controlled experimental and computational methods.

Keywords:

Structure transformation, Coalescence, Repulsion, Size-dynamics

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