Interactions between clusters of self-interstitial atoms via a conservative climb in BCC–Fe

Sho Hayakawa\textsuperscript{a}, Taira Okita\textsuperscript{b}, Mitsuhiro Itakura\textsuperscript{c}, Masaatsu Aichi\textsuperscript{b} and Katsuyuki Suzuki\textsuperscript{b}

\textsuperscript{a}School of Engineering, University of Tokyo, Tokyo, Japan; \textsuperscript{b}Research into Artifacts, Center for Engineering, University of Tokyo, Kashiwa, Japan; \textsuperscript{c}Center for Computational Science & e-Systems, Japan Atomic Energy Agency, Kashiwa, Japan

ABSTRACT

We conduct kinetic Monte Carlo simulations for the conservative climb motion of a cluster of self-interstitial atoms (SIAs) towards another SIA cluster in BCC–Fe; the conservative climb velocity is inversely proportional to the fourth power of the distance between them, as per the prediction based on Einstein’s equation. The size of the climbing cluster significantly affects its conservative climb velocity, while the size of the cluster that originates the stress field does not. The activation energy for the conservative climb is considerably greater than that derived in previous studies and strongly dependent on the climbing cluster size. The results presented in this study are the atomistic evaluation of the behaviour of SIA clusters through three-dimensional motion, which cannot be achieved using molecular dynamics techniques alone.

1. Introduction

Self-interstitial atoms (SIAs) are only formed under high-energy particle irradiation; therefore, the behaviour of them and their clusters is a key factor for predicting the radiation-induced property changes of nuclear materials [1]. The kinetics of this behaviour has been extensively studied by molecular dynamics (MD) simulations and is dependent on the cluster size. For instance, in BCC–Fe, single SIAs and clusters composed of up to 3–4 SIAs can be mobile three-dimensionally, even in the MD timescale [2,3]. This results in a relatively large cross-section for interaction with other defects, enhancing the cluster growth and recombination with vacancies. Larger clusters can glide one-dimensionally with very low activation energy [2–4], causing the long-range mass transport of the clusters; in some cases, they escape from their original cascade regions without significant interaction with vacancies [5]. Meanwhile,
There are several experimental reports, where the three-dimensional motion of relatively large defect clusters was also observed, during the post-irradiation annealing of Al [6], UO₂ [7], and Mo [8], post-quenched annealing of Al–Mg alloy [9] and Al [10], and in the in-situ ion irradiation of Fe [11] and Zr [12]. These motions occurred gradually, in a time lapse ranging from several microseconds to hours, i.e. on a timescale inaccessible to MD techniques. Additionally, they occurred either without Burgers vector flipping or a change in cluster size. This confirms that they are conservative climb motions, known as the mass transport caused by pipe-diffusions of the composing atoms around the cluster periphery. Conservative climb renders the cluster cross-section considerably larger for inter-defect interaction, consequently accelerating the growth and coalescence of defect clusters, and cluster annihilation at sinks, such as dislocations. Furthermore, a detailed kinetic Monte Carlo (KMC) study has shown that the three-dimensional motion of defect clusters is an essential mechanism for modelling the damage accumulation after cascade events; without incorporating the motion, a discrepancy of several orders of magnitude in the defect concentration was observed between the simulation and experimental results [13]. Therefore, the conservative climb is a critical kinetics for describing microstructural evolution under irradiation, and is necessary for quantifying the motion to provide precise input parameters for coarse-grained models, for long-term microstructural evolution.

Theoretical approaches were utilised to model the conservative climb, where the elasticity theory was used to describe the stress field around the cluster [14,15]. In these models, several assumptions were made for simplicity, neglecting the atomistic description of pipe-diffusions, although they are the elementary processes of the conservative climb. Only one MD study had demonstrated the conservative climb of an SIA cluster towards another in BCC–Fe [16]. However, this atomistic study was conducted under very specific conditions, namely, at a very high temperature (around 1000 K) and at a very short distance between the two clusters. This result demonstrates that it is difficult to develop a comprehensive model of the conservative climb using MD techniques only.

An atomistic model of the conservative climb was recently developed by Swinburne et al. using molecular statistic (MS) and KMC techniques [17]. In this model, numerous MS simulations and nudged elastic band calculations were performed, extracting simple equations for describing the activation energy for the migration of an atom along the cluster edges and the change in system energy due to the migration. This enabled the easy modelling of the migration process, by counting the number of first nearest neighbours of the migrating atom, without any geometric information around the migrating atom (Here, ‘geometric information’ indicates the relative position relationships between the migrating atom and the first nearest neighbours). With these equations, KMC simulations were performed and the diffusivity of the cluster through conservative climb was evaluated. Although the extracted migration
energy and the change in system energy may not be precise due to the use of simplified equations, their model succeeded in describing the conservative climb with the atomistic description of the climb process (The precision of simplified equations, i.e. the effect of the lack of atomic geometric information, will be discussed in Section 2.2., in detail.)

Our group had also developed a model of the conservative climb of an SIA cluster, incorporating the atomistic behaviour [18]. In this model, the KMC algorithm was used for describing the cluster behaviour, whereas the input parameters were derived using MS/MD simulations. Additionally, we considered the geometric information around the migrating atom for describing its activation energy and assigned different values to geometrically different migration patterns, resulting in a precise evaluation of the conservative climb. Coupling the KMC and the MS/MD techniques, we overcame the timescale problem that would have occurred with MD techniques alone, while maintaining the precision of the atom migration as well as its activation energy. Using this model, we simulated the absorption process of an SIA cluster by an edge dislocation in BCC–Fe [18,19].

Here, we present the KMC simulations of the conservative climb of an SIA cluster towards another SIA cluster in BCC–Fe, which is the base material for structural applications in the nuclear industry. The model developed in our recent work is applied in the simulations [18], and the case of SIA clusters with parallel Burgers vectors is studied because the elastic interaction is the strongest and hence the probability of the coalescing of the clusters via conservative climb is higher in this case [20]. We consider the change in the habit plane owing to the stress field originating from the other cluster, which affects the distance between the clusters [21,22]. We discuss the conservative climb velocity of the cluster from the perspective of its dependence on the distance between the two clusters and their sizes. We also quantify the relative velocity of one cluster with respect to the other. The activation energy of the conservative climb and its dependence on the cluster size are discussed, as well.

The rest of this paper is organised as follows: The basic concept of the model and the method for deriving the necessary parameters with MS/MD simulations are described in Section 2. The KMC simulation results are presented and discussed in Section 3. Finally, conclusions are drawn in Section 4.

2. Simulation method

As the conservative climb model has been described in detail in the earlier work [18], we provide a brief explanation of the model here. We set two hexagonal SIA clusters with parallel Burgers vectors; they are represented by the smaller and larger clusters in Figure 1(a). For the smaller cluster, the number of atoms on the edge (l) was set to 4, 5, 6, or 7; we initially placed 4, 6, 8, or 10 extra atoms on the edges, respectively (Figure 1(b)). These atoms enhance the
conservative climb significantly. For the larger cluster, $l$ was varied from 4 to 15. As seen in the results section, the conservative climb velocity drastically decreases as the size of the smaller cluster increases; hence, the larger cluster was assumed to be the origin of the stress field that induces the conservative climb of the smaller one only and it was not allowed to move via the conservative climb, unless mentioned otherwise.

2.1. Basic concept of the conservative climb model

We have modelled the migration process of a single atom on the outermost layer of the smaller cluster along the cluster edges, through which the cluster changes shape, resulting in a conservative climb. The activation energy for the migration, $E_a$, was evaluated by MS or MD simulations for BCC–Fe; the detailed procedure is described in the following subsection. Two assumptions were made for the simulation of the migration process: First, an atom on the hexagonal edge cannot exist in a double-layered structure; i.e. an atom can migrate only on the red and yellow dotted lines in Figure 2(a). This restriction for atom mobility was set for simplicity. Next, all atoms (except those at the corners) must be in contact with two adjacent inner atoms. A corner atom, surrounded by one adjacent inner atom and two neighbouring atoms on the edges, must have contact with the adjacent inner atom and at least one of the two neighbouring atoms (Figure 2(b)). This assumption is necessary because an atom that does not meet this condition would be unstable. Migration events that do not follow these two assumptions were not permitted.

At each step, all the possible migration patterns were examined and one of them was chosen, using the KMC algorithm. For the time evolution of the chosen migration, the residence time algorithm was applied, based on the

Figure 1. (a) Smaller and larger cluster, whose Burgers vectors are in parallel and (b) view from the direction perpendicular to their habit planes. Extra atoms are initially placed on the edges of the smaller cluster.
The frequency of the migration is derived as:

$$\nu = \nu_0 \exp\left(\frac{-E_a}{kT}\right),$$  \hspace{1cm} (1)

where $\nu_0$, $T$ and $k$ are the pre-exponential factor, temperature and Boltzmann’s constant, respectively. The expression for $E_a$ is given in Section 2.2. The value of $\nu_0$ was set to $10^{13}$ Hz and $T$ was varied from 673 to 1073 K, in this simulation.

After each migrational event, the occurrence of the conservative climb was evaluated. We tentatively set the new centre of the smaller cluster at one of the neighbouring atoms of the original centre that were nearer the other cluster; then, the hexagonal edges were drawn with the new centre. (The hexagonal edges correspond to the red and yellow dotted lines in Figure 2.) If these procedures reduced the sum of the number of atoms on the edges, we assumed that by definition conservative climb had occurred. If setting the new centre did not follow the first assumption for the migration process, we did not assume that conservative climb had occurred.

Figure 3 shows the spatial relationship between these two clusters. Centring around the stable position, the clusters glide back and forth within the cylinder; hence, we assumed that the distance between the clusters, along the glide direction ($h_{\text{glide}}$), can be represented by that in the stable position, and did not explicitly incorporate the motion. The habit planes of both clusters change as a consequence of the stress field originating from the other cluster, where the angles between the habit plane and the Burgers vector are denoted by $\theta_1$ and $\theta_2$ for the smaller and larger clusters, respectively. The values of $h_{\text{glide}}$, $\theta_1$, and
\( \theta_2 \) were evaluated using the elasticity theory by minimising the sum of the interaction energy and self-energy [21,22]. The distance between the centres of the larger and smaller clusters along the climb direction, denoted by \( h_{\text{climb}} \), was varied from 4.9 to 10.1 nm, every 0.2 nm. According to Trinkaus et al., the two clusters start to trap each other, when the interaction energy is nearly \( kT \) \((h_{\text{climb}} \sim 9–11 \text{ nm meets this condition at} 673–1073 \text{ K})\); the value of \( h_{\text{climb}} \) that meets this condition is the maximum distance, where conservative climb can occur. In each condition, 400 repeated KMC simulations were performed, and the average velocity was obtained at each \( h_{\text{climb}} \).

### 2.2. Activation energy for migration

We assumed that \( E_a \) is described as:

\[
E_a = E_m + \frac{\Delta E_{\text{int}} + \Delta E_{\text{tot}}}{2},
\]

where \( E_m \) is the activation energy for the pipe-diffusion of an atom, \( \Delta E_{\text{int}} \) is the change in the interaction energy of the migrating atom with the stress field originating from the other cluster, due to a migrational displacement of the atom. \( \Delta E_{\text{tot}} \) is, finally, the change in the system energy caused by a change in the cluster shape due to a migration event. These values were derived with MS and MD simulations, using the interatomic potential developed by Mendelev et al. [24]. For the MS/MD simulations, the simulation cell was set to \([-2 1 1] \) 4.1 nm \( \times \) \([0 1 -1] \) 4.4 nm \( \times \) \([1 1 1] \) 3.6 nm for the x, y and z directions, respectively. Periodic boundary conditions were employed in all the directions. We inserted three extra \( x-y \) planes, with rectangular strips of approximately 4.1 nm \( \times \) 2.0 nm, in the centre of the cell to simulate the cluster edge (Figure 4).

To derive the value of \( E_m \), we placed an extra atom or a vacant site along the edge of the planes and counted its number of jumps along the edge at 1100, 1200,
1350 and 1500 K, using MD. From the jump frequency measured from the simulation, the value of $E_m$ was evaluated to be 1.02 eV.

For evaluating $E_{\text{int}}$, we used the following equation:

$$E_{\text{int}} = V_H \cdot \sigma_H + V_{[111]} \cdot \sigma_{[111]},$$

(3)

where, $\sigma_H$ and $\sigma_{[111]}$ denote the hydrostatic and [1 1 1] uniaxial stress components, respectively. The coefficients, $V_H$ and $V_{[111]}$, were estimated to be $2.15 \times 10^{-30}$ and $1.51 \times 10^{-29}$ m$^3$, respectively, by calculating the change in the formation energy of an SIA along the edge of the planes, with respect to the local stress. An isotropic elasticity calculation, with an effective isotropic shear modulus of 65.5 GPa and Poisson’s ratio of 0.323, was used to obtain $\sigma_H$ and $\sigma_{[111]}$ at each position [25]. The value of $\Delta E_{\text{int}}$ was defined as the difference in $E_{\text{int}}$ between the positions before and after atom migration, which is the driving force of the conservative climb.

There are five possible configurations involving $\Delta E_{\text{tot}}$, owing to a migrational displacement of an atom along the cluster edges, which are shown in Figure 5 (a)–(e). The system energy in the initial and final relaxed states was calculated and the difference between them was defined as $\Delta E_{\text{tot}}$. The values of

![Figure 4. Schematic of the MS/MD simulation cell.](image)

![Figure 5. (a) Possible configurations that involve a change in $\Delta E_{\text{tot}}$ (a) along a line, (b)–(e) at a jog, and (f)–(g) at a corner. (a) $\Delta E_{\text{tot}} = 1.74$ [eV]; (b) $\Delta E_{\text{tot}} = 1.03$ [eV]; (c) $\Delta E_{\text{tot}} = 0.91$ [eV]; (d) $\Delta E_{\text{tot}} = 0.30$ [eV]; (e) $\Delta E_{\text{tot}} = 0.72$ [eV]; (f) $\Delta E_{\text{tot}} = 0.30$ [eV]; (g) $\Delta E_{\text{tot}} = 0.91$ [eV].](image)
$\Delta E_{tot}$ at the corner of the cluster were evaluated using the values along the edge (Figure 5(f,g)).

Note that the difference in $\Delta E_{tot}$ between the patterns of Figure 5(b,e) was as high as 0.31 eV, although the difference in the number of bonding with the first nearest neighbours, before and after migration ($\Delta c$), was the same ($\Delta c = -1$). Furthermore, even in the case of $\Delta c = 0$, $E_{tot}$ was observed to increase; $\Delta E_{tot}$ for the pattern of Figure 5(d) was 0.30 eV. This is because this migration renders the plane shape more dissimilar from a few-jog configuration (in principle, the most energetically stable plane configuration is the one with as few jogs as possible). These indicate that the detailed geometry around the migrating atom affects its migration process; hence, it is important to incorporate the geometric information for precisely modelling the migration process.

The values of $E_m$, $\Delta E_{int}$ and $\Delta E_{tot}$, derived with MS/MD simulations, were used as the input parameters for Equation (2).

### 3. Results and discussion

In subsections 3.1. and 3.2., we discuss the dependence of the smaller cluster velocity on three parameters: the distance between the two clusters, the size of the smaller cluster, and that of the larger cluster. In these subsections, we assume that the larger cluster does not move through a conservative climb. The relative velocity of one cluster with respect to the other is evaluated in subsection 3.3., where we consider the conservative climb of the larger cluster. Finally, we discuss the activation energy for the conservative climb, in subsection 3.4. Hereafter, the diameters of the smaller and larger clusters are denoted as $d_{smaller}$ and $d_{larger}$, respectively, and the average velocities of the clusters, derived by repeated simulations, are denoted as $v_{smaller}$ and $v_{larger}$, respectively.

#### 3.1. Dependence of the velocity on the distance between the two clusters

Figure 6 depicts $v_{smaller}$ as a function of $h_{climb}$ when $T$, $d_{smaller}$ and $d_{larger}$ are set to 873 K, 1.63 ($l = 4$) nm and 3.96 ($l = 9$) nm, respectively. The value of $v_{smaller}$ is found to be inversely proportional to the fourth power of $h_{climb}$. Note that, according to the isotropic elasticity, the magnitude of the stress originating from the larger cluster, which is proportional to $E_{int}$ (see Equation (3)), is inversely proportional to the third power of the distance between the clusters [25]. Hence, the inverse fourth power dependence is the same as that predicted by the Einstein equation, where $D$, $k$ and $T$ are the diffusion coefficient, Boltzmann’s constant, and temperature, respectively (Equation (4)). Together with the fact that the dependence of the conservative climb velocity of an SIA cluster towards an edge dislocation follows the Einstein equation [18,19], it is thus possible to treat the conservative climb of a cluster as a simple diffusion process.
under a gradient in the stress field.

\[ v_{\text{smaller}} = \frac{D \partial E_{\text{int}}}{kT \partial x}. \] (4)

### 3.2. Dependence of the velocity on the cluster sizes

Figure 7(a) shows \( v_{\text{smaller}} \) as a function of \( d_{\text{smaller}} \) at \( T = 873 \) [K], \( h_{\text{climb}} = 8.09 \) [nm] and \( d_{\text{larger}} = 3.97 \) [nm] \((l = 9)\). It is apparent that \( v_{\text{smaller}} \) decreases drastically as \( d_{\text{smaller}} \) increases. A replotted figure with logarithmic scales is shown in Figure 7(b). It can be deduced that \( v_{\text{smaller}} \) is approximately proportional to the inverse ninth power of \( d_{\text{smaller}} \). In addition, nearly the same \( v_{\text{smaller}} \) value and dependence were obtained at \( d_{\text{larger}} = 5.36 \) [nm] \((l = 12)\) and 6.76 [nm] \((l = 15)\). The inverse ninth-power dependence is considerably stronger than the prediction based on the dislocation theory, where \( v_{\text{smaller}} \) is proportional to the inverse fifth power of \( d_{\text{smaller}} \) owing to two size-dependent factors: the gradient in the defect concentration around the cluster due to the stress field originating from the other cluster, leading to the inverse fourth power dependence, and the number of migrating atoms necessary for occupying the closest edge of the smaller cluster to the origin of the stress field, leading to an inverse dependence \([15]\). However, in the atomistic scale, another size-dependent factor surpasses these two factors: the probability of an atom having jumped onto the edge to undergo an energetically preferable recombination with the vacant site, where the atom was originally located. This probability becomes higher on increasing \( d_{\text{smaller}} \), and such a recombination causes a significant reduction in the number of atoms that contribute to the conservative climb. (The detailed mechanism is presented in Ref. \([18]\).) A stronger dependence was also observed for the conservative climb of an SIA cluster towards an edge dislocation, where an inverse eighth-power dependence was obtained \([18]\).
Figure 8 shows $v_{\text{smaller}}$ as a function of the gradient in $E_{\text{int}}$, when $T$, $h_{\text{climb}}$ and $d_{\text{smaller}}$ were set to 873 K, 8.09 nm and 1.63 nm ($l = 4$), respectively. The gradient in $E_{\text{int}}$ was derived by the difference in $E_{\text{int}}$ between the edges nearest and farthest from the origin of the stress field, divided by the distance between the two edges. Note that, in the isotropic elasticity theory, $E_{\text{int}}$ is proportional to the square of $d_{\text{larger}}$, depicted in the upper horizontal axis. Although $v_{\text{smaller}}$ is found to be proportional to the square of $d_{\text{larger}}$, the absolute value does not
depend strongly on $d_{\text{larger}}$; it is of the same order. The velocity towards an edge dislocation, plotted in the figure with a square symbol, has a similar value as those towards the larger cluster [18]. These results indicate that $v_{\text{smaller}}$ is determined mainly by $d_{\text{smaller}}$, rather than the origin of the stress field, in either the case of a cluster of any size or a dislocation.

3.3. Relative velocity between the two clusters

As the time for calculating $v_{\text{larger}}$ with $d_{\text{larger}} > 3.03$ nm ($l > 7$) would be extensive, they were derived by the extrapolation of $v_{\text{larger}}$ with $d_{\text{larger}}$ ranging from 1.63 to 3.03 nm ($l = 4$–7), with an inverse ninth-power dependence of the cluster size, based on the results shown in subsection 3.2.

Figure 9 shows the dependence of the relative velocity on $d_{\text{larger}}$, when $T$, $h_{\text{climb}}$ and $d_{\text{smaller}}$ were set to 873 K, 8.09 nm and 1.63 nm ($l = 4$), respectively. When $d_{\text{larger}}$ was set to be the same as $d_{\text{smaller}}$ ($d_{\text{larger}} = 1.63$ nm), the relative velocity was very high. This is because the conservative climb of both the clusters is significant. When $d_{\text{larger}}$ increased, the relative velocity dropped drastically, owing to the considerable decrease in $v_{\text{larger}}$ on increasing $d_{\text{larger}}$ (see the first paragraph of subsection 3.2.). Once the velocity dropped, it hardly changed, as $d_{\text{larger}}$ increased further. In this region, $v_{\text{larger}}$ is negligible compared to $v_{\text{smaller}}$, hence, the relative velocity is determined mainly by $v_{\text{smaller}}$. This indicates that $d_{\text{smaller}}$ is the controlling parameter in determining the time required for the coalescence of two SIA clusters through the conservative climb.

3.4. Activation energy for the conservative climb

The frequency of the conservative climb on a logarithmic scale is depicted as a function of the temperature in Figure 10. The values of $h_{\text{climb}}$ and $d_{\text{larger}}$ were set to 6.07 and 5.84 nm ($l = 13$), respectively, and here we define one conservative climb as one atomic distance movement of the cluster centre. From Figure 10,

![Figure 9](image-url)
the activation energy for the conservative climb ($E_{cc}$) can be evaluated using the Arrhenius law based on the Einstein equation: $E_{cc} = 1.82, 2.05$ and $2.24$ eV for $d_{smaller} = 1.63, 2.10$ and $2.57$ nm, respectively, which are comparable to those obtained in our earlier work [18]. In addition, we evaluated $E_{cc}$ by changing $d_{larger}$ to $2.10$ ($l = 5$) and $3.97$ nm ($l = 9$); in both cases, $E_{cc}$ differed from the values mentioned above by not more than an order of $0.01$ eV.

The values of $E_{cc}$ obtained in this study are much higher than the predicted values based on the elasticity theory, where $E_{cc}$ was anticipated to be equivalent to the activation energy of the individual atom migration along the cluster edge, namely, $E_m (= 1.02$ eV), and was even independent of $d_{smaller}$ [15,26]. The obtained values are higher than even $1.34$ eV, derived using the equation suggested by Swinburne et al. [17]. This is partly because of the treatment of the atom migration process. We treated each possible migration pattern separately, enabling the precise evaluation of the activation energy for the migration and the improvement of the model fidelity. Another factor that could cause the differences is the first assumption in the migration process of an atom (see subsection 2.1.). Such restriction would decrease atom mobility to a certain extent, possibly causing the more energetically preferable migration paths to be overlooked.

The results presented here include another interesting implication. The recently developed atomistic models of the conservative climb, namely, our model [18] and that developed by Swinburne et al. [17], are based on the assumption that the migration of a single atom along the cluster edges is an elementary process of the conservative climb. However, considering that restrictions for atom migration could affect the activation energy for the conservative climb, there is also a possibility that lower activation energy, even below the value obtained by Swinburne et al., can be obtained by removing the restriction that forbids the concurrent migration of several atoms in one step, which we leave for a future study.

**Figure 10.** Frequency of the conservative climb as a function of the temperature, when $h_{climb}$ and $d_{larger}$ are set to 6.07 nm and 5.84 nm ($l = 13$), respectively.
4. Conclusions

KMC simulations were performed to simulate the conservative climb of an SIA cluster towards another, in BCC–Fe. A total of 400 repeated simulations were performed in each condition.

The value of $v_{\text{smaller}}$ was found to be dependent on the inverse fourth power of $h_{\text{climb}}$, which is the same dependence as that derived from the Einstein equation. It was also found that $v_{\text{smaller}}$ was inversely proportional to the ninth power of $d_{\text{smaller}}$, which is a much stronger dependence than that obtained by the dislocation theory. On the other hand, the value of $d_{\text{larger}}$ did not affect $v_{\text{smaller}}$ considerably. These results lead to the conclusion that the smaller cluster size controls the required time for the two SIA clusters to coalesce through the conservative climb. The activation energy for the conservative climb was evaluated; they were considerably higher than those obtained in previous studies and a strong dependence on the climbing cluster size was observed.

The results presented here are the quantitative evaluation of the interaction between SIA clusters via the conservative climb, based on atomistic behaviour, which occurs on a timescale that cannot be handled by MD techniques. They can be used as input parameters for a model that can predict the microstructural evolution in BCC–Fe under irradiation, in which the behaviour of SIA clusters is an essential factor.

Acknowledgements

We would like to thank Editage (www.editage.jp) for the English language editing.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by Chubu Electric Power Co., JSPS KAKENHI Grant Numbers: JP17H03518 and JP17KT0039, and JSPS Overseas Challenge Program for Young Researchers.

References

