Influence of antidots on the critical current density of HTSC in a magnetic field

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Abstract. By using the Monte Carlo method, a numerical study has been conducted to calculate the current-voltage characteristics of a high-temperature superconductor with intrinsic pinning sites and the additional ones in the form of antidots in different magnetic fields. Various types of antidot distribution among the sample such as a random distribution, triangular and square lattice and their conformal transformations, have been considered. Descending critical current density dependencies on the magnetic field for different samples have been acquired. Averaged vortex configurations of samples for different antidot distributions at the same magnetic field and transport current have been acquired. The most effective antidot distribution has been determined.

1. Introduction
Today high-temperature superconductors (HTSC) draw more and more attention to themselves. A vast amount of studies is devoted to finding the methods of increasing the critical current density $J_c$ of HTSC. A great number of various methods is known today, and one of the newly discovered ones is the method of patterning superconductors with arrays of through or blind holes called the antidots [1–6]. Generally, those antidots are nanometer or submicrometer holes of different shapes distributed among the sample in a certain periodic way. Multiple research groups have shown that the presence of such antidots may significantly increase the transport characteristics of an HTSC [1–4]. The investigations of HTSCs with antidots in magnetic fields are especially relevant [5–6].

In this paper, we have conducted some numerical simulations of the influence of antidots and the type of their distribution among the sample on the critical current density of an HTSC in presence of a magnetic field.

2. Model for calculations
All calculations have been carried out within the limits of the model of a layered HTSC by using an algorithm based on the continual Monte Carlo method [7–10]. This model allows to carry out calculations of magnetic and transport characteristics of 2D and 3D layered HTSC and has already been repeatedly used, for example, in papers [9–10].

The principle of operation of the algorithm lies in the minimization of the Gibbs potential of a two-dimensional system with alternating number of vortices that can be described by (1). It consists of a sum of the vortex self-energies as well as the energy of their interactions with each other, the sample surface, external magnetic field, transport current and various pinning sites. For more detailed information see [7–8].
In our model, the antidots are cylindrical through holes about 300 nm in diameter. Each antidot is surrounded by a ring of columnar defects which appear in real samples when the antidots are fabricated. Thus, the interaction of vortices with the antidots consists of their interaction with the border and with the columnar defects.

\[ G = \sum_{i<j} U(r_{ij}) + \sum_{i} U_{pn}(r_{ij}) + \sum_{i\neq j} U_{surf}(|r_{ij} - r_{ij}^{image}|) + \sum_{i} U_{m}(x_{i}) + N\varepsilon \]  

A BSCCO superconductor (\(\lambda = 180\) nm, \(\xi = 2\) nm, \(T_c = 84\) K) of the size of 5 \(\mu\)m \(\times\) 5 \(\mu\)m with the two-dimensional density of randomly distributed defects of approximately \(4 \times 10^8\) cm\(^{-2}\) has been chosen as a sample for calculations. Various types of antidot distribution have been considered such as: a random distribution, triangular and square lattices and their conformal transformations (for the latter see [3–4]). In all types of distributions, the total amount of antidots is approximately the same and amounts to 50. All calculations have been carried out in different magnetic fields varying from 0 to 1000 Oe at helium temperatures. The critical current density \(J_c\) was determined by the standard electric field criterion of 1 \(\mu\)V/cm.

3. Results

Figure 1 shows series of current-voltage characteristics (CVC) of samples with different types of antidot distributions ((a) triangular lattice, (b) square lattice, (c) random distribution) and a sample with no antidots (d) in different magnetic fields. It is obvious from the picture that the critical current density \(J_c\) decreases with the increasing magnetic field. Also, when comparing the pictures for different distributions with one another one may notice that the extent of this decrease varies in different cases.

![Figure 1](image)

**Figure 1.** Series of current-voltage characteristics of samples with different types of antidot distribution: (a) triangular lattice; (b) square lattice; (c) random distribution; (d) no antidots, in different external magnetic fields.

This is clearly demonstrated in figure 2 where the acquired critical current density dependency on the external magnetic field for different types of antidot distribution including the sample with no
antidots. It can be seen from the picture that the critical current density increases when antidots are added to the sample: it amounts up to approximately 15–20% for the conformal transformation of a triangular lattice of antidots. One may also notice that, though for weak magnetic fields different types of antidot distribution provide approximately the same result (in the left of figure 2), in strong magnetic fields the difference becomes quite significant. Thus, the conformal transformations of triangular and square lattices gave for the best critical current density resistance to the magnetic field (at $H = 1000$ Oe $J_c$ dropped by approximately 25%) whereas the square lattice of antidots gave for the worst result (at the same conditions, $J_c$ dropped by approximately 50%). Such a result is in qualitative correspondence with experimental data.

![Figure 2](image)

**Figure 2.** The calculated critical current density dependencies on the external magnetic field for different types of antidot distributions among the sample.

To demonstrate the influence of antidots and the type of their distribution on the vortex dynamics, averaged vortex configurations have been acquired for a magnetic field of 250 Oe and the transport current density of 0.74 MA/cm$^2$. They are demonstrated in figure 3. As was the case for figure 1, (a) is for the triangular antidot lattice, (b) is for the square lattice, (c) is for random distribution and (d) is for no antidots at all. It should be noted that in the cases of (a) and (b) the transport current density is lower than the critical value, in the case of (c) it is approximately equal to it and in the case of (d) it is much higher than $J_c$.

It can be seen from the picture that for the same current density the vortices enter the sample and move through it differently. In the sample with a triangular antidot lattice (a), the vortices got pinned by the antidots and defects near the sample border, and because of the repulsive interaction of vortices with one another, they prevent other vortices from entering the center of the sample. As a result, some of the antidots in the sample center were left unoccupied by vortices.

In the case of a square lattice (b) and a random distribution (c) of antidots, a similar situation is observed, however the distance between neighboring antidots is bigger than in the case of a triangular lattice (a), and the vortices are able to seep into the sample center between the occupied antidots. This is clearly demonstrated by thick lines (vortex tracks) in figures 3 (b) and (c). It should also be noted that in the cases of (b) and (c) almost all antidots are occupied by vortices.

In the case of the sample with no antidots (d) all the vortex pinning occurs on defects, and at the same current density the vortices move much more actively than in the case of a square antidot lattice (b). Thus, the antidots act as an additional effective pinning mechanism and increase the critical current density.
Figure 3. The averaged vortex configurations of samples with different antidot distributions in a magnetic field $H = 250$ Oe with the transport current density $J = 0.74$ MA/cm$^2$. (a) is for the triangular antidot lattice, (b) is for the square antidot lattice, (c) is for the random antidot distribution and (d) is for a sample with no antidots.

4. Conclusion
The vortex system of a layered high-temperature superconductor with intrinsic and artificial pinning centers in the form of antidots has been numerically studied in external magnetic fields and in the presence of a transport current. Different types of antidot distribution among the sample have been considered in order to determine the most optimal choice. The highest critical current density as well as its resistance to the external magnetic field was provided by the conformal transformations of a triangular and square antidot lattices.

It has been demonstrated that the vortex system behaves differently in samples with different antidot distributions in the presence of a magnetic field. The triangular lattice turned out to be more effective in terms of vortex pinning than the square lattice or a random distribution. When comparing the results with the ones for a sample with no antidots, it has been shown that the antidots contribute to the pinning potential of the superconductor thus increasing the critical current density.

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