CRITICAL CURRENT ENHANCEMENT USING HOLES

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ABSTRACT

The critical current densities of superconductor having arrays of square holes and lines hole exposed under electric and perpendicular magnetic field are calculated using time dependent Ginzburg-Landau equation (TDGLE). The result shows that the addition of an array of hole and lines hole enhance the critical current density through different pinning mechanism. The enhancement of critical current by an array of hole addition enhances the critical current densities through commensurate effect and produces the critical current peaks at matching magnetic fields while the addition lines hole to superconductor enhances the critical current through a simple pinning but covering a wider magnetic region. The enhancement factors produced by the both holes are discussed.

Keywords: *Superconductor, Time dependent Ginzburg-Landau, Two dimensions, Holes, Critical current*

Makalah diterima [tanggal bulan tahun]. Revisi akhir [tanggal bulan tahun].

I. INTRODUCTION

The critical current is one of the important quantities in superconductor. Much effort was done to increase the critical current densities such as using heavy particles irradiation (Aytug et.al., 2006), neutron irradiation (Pallecchi et.al., 2005), surface defects, and an array of hole added to superconductor (Kemmler et.al.,2005). It was understood that to enhance the critical current requires a strong pinning force to resist the vortices motion. Numerical studies in determining the critical current enhancement using defects were done using TDGLE (Machida and Kaburaki, 1994; Winiecki and Adam, 2002), but only the calculation done using molecular dynamics on superconductor having hole arrays (Misko et.al.,2006) showing close result to experiment especially in enhancing the critical current through commensurate effect. Both experiment and numerical result shows that the critical current increase significantly at commensurate fields but decreases considerably at other magnetic fields (Raedts et.al., 2004; Silhanek et.al., 2005). Therefore another improvement is still required to maintain the critical current high beyond the commensurate fields. In improving the method of determining the critical current and in searching an alternative way to increase the critical current that possibly cover a wider magnetic field, in this contribution we investigate the critical current enhancement on superconductor having an array of hole and a lines hole perpendicular to vortices motion by first solving the TDGLE. In determining the critical current density, we purpose a minimum vortices motion criterion instead of the usual electric field cut-off criterion at the $E-J$ curve.

II. MODEL

The standard dimensionless TDGL form can be written as (Harsojo et.al. 2004)

$$\partial_t \Psi = \tfrac{1}{12}\left(-i\nabla - \mathbf{A}\right)^2 \Psi + (1-T)\left(\left|\Psi\right|^2 - 1\right)\Psi \qquad (1)$$

which is coupled with super current

$$\mathbf{J_S} = \tfrac{1}{2}(\Psi^* \nabla \Psi - \Psi \nabla \Psi^*) - \left|\Psi\right|^2 \mathbf{A}\,, \qquad (2)$$

where $\mathbf{J} = \mathbf{J}_n + \mathbf{J}_s$ is the total current density. In the dimensionless unit magnetic field has $H_{c2}(0)$, the length is expresses in $\xi(0)$ (the coherence length at temperature $T = 0$), temperature in unit T_c (the critical temperature), and time is expressed in unit $\tau_0 = 4\pi\sigma\lambda(0)^2 / c^2$. Here the normal current is $\mathbf{J}_n = -\partial_t \mathbf{A}$. To accommodate the existence of holes, we have to imply the proper boundary condition for magnetic field $B_z = (\nabla \times \mathbf{A}) \bullet \hat{z} = H$ on the surface of the superconductor as the external magnetic field is on the z-direction while the density current flows on the *x*-direction such that $\hat{x} \bullet (i\nabla - \mathbf{A})\Psi = -J_t$, while $\hat{y} \bullet (i\nabla - \mathbf{A})\Psi = 0$ where $\hat{x}$ and $\hat{y}$ is unit normal vectors. Such a boundary condition is implemented at the edges of superconductor. At each square hole, we use the boundary condition such that $\hat{n} \bullet (i\nabla - \mathbf{A})\Psi = 0$ is also implemented. Here $\hat{n}$ is a normal unit vector. Inside the holes, the magnetic field H_i is equal to external magnetic field H_e while at the boundary between the superconductor and the holes satisfy $B_z = H_i$. When the superconductor having an array of hole is exposed under vertical magnetic field, there exists commensurate phenomenon in which the total magnetic flux matches with the lattice hole cell. In this situation, the matching magnetic fields are $H_n = n\frac{\Phi o}{S}$ where Φ_o is the flux unit, S is the size of the cell, and n is an integer or fractional number. In such magnetic fields, vortices will arrange themselves to be stable by sitting at the holes and the lattice holes edges. The first matching field is related to the vortices occupy the holes while the second matching field is related to the condition where the vortices occupy both the middle of edges of the holes array and the holes. Having an external current added to the sample, some extra boundary shall be managed such that the first derivative of the normal scalar field zero and the local magnetic field will contain the sum of external magnetic field and the current induced magnetic field. This boundary condition is taken by assuming that the superconductor material is bounded by the normal materials at side edges where the electric current flows. Having this done in two dimensions approach and using finite difference approximation for space and using linear integration in time, we calculate the critical current density at a certain magnetic field which is determined using the criteria of minimum vortices motion. This is done by looking at that the smallest constant voltage produced in reaching the vortices stability when the superconductor is exposed on electric current and

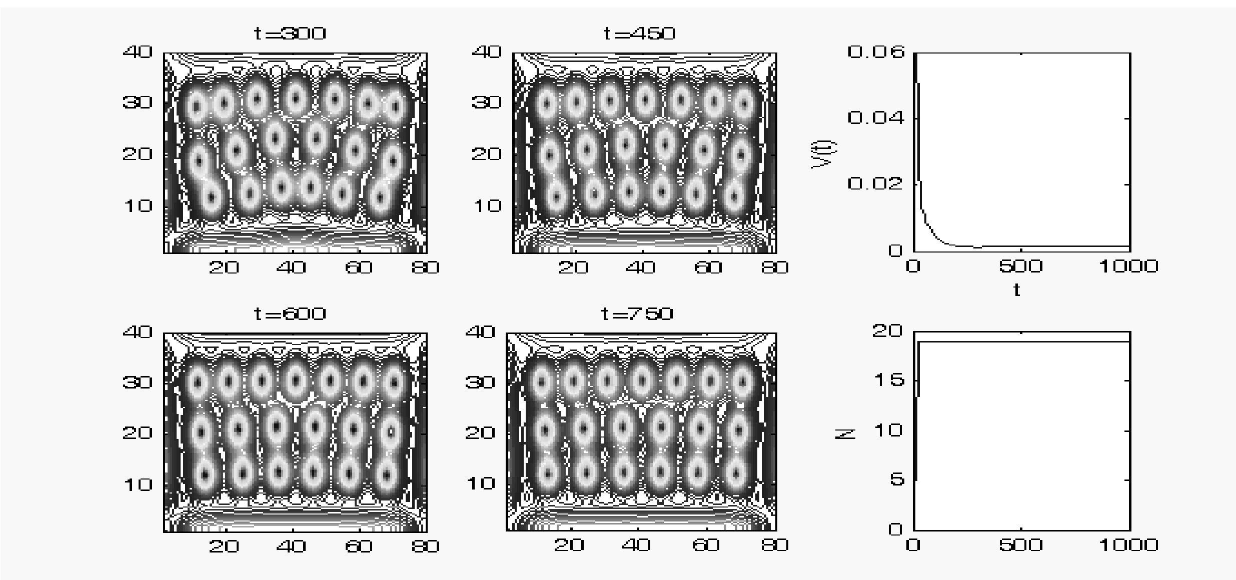

Figure 1: The example of critical condition on superconductor without holes. The configuration of vortices is presented by contour of $|\Psi(x, y)|$ which is stable as time grows and the related constant electric voltage $V(t)$ at critical condition. N is the number of vortex. The size of superconductor is 20×40. The picture is taken at $H = 0{,}3$ and $j_c = 0{,}007$ in dimensionless unit.

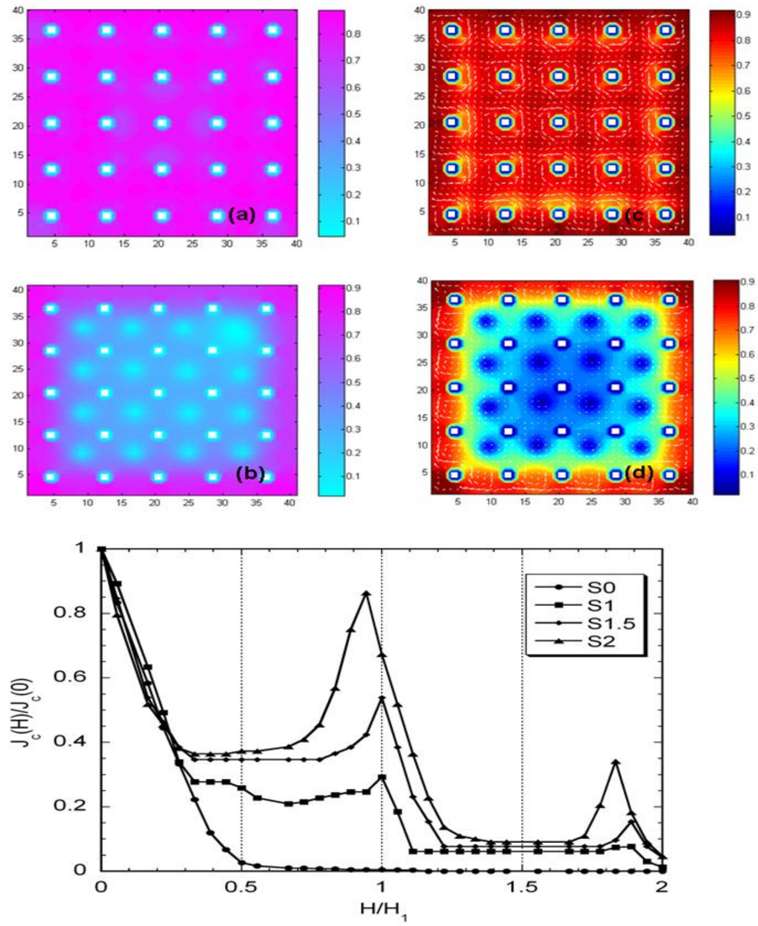

Figure 2: The contour of $|\Psi(x,y)|$ shows the supercharge density at matching magnetic field (a) $H_1 = 0{,}4$, $j = 0$, (b) $H_2 = 0{,}8$, $j = 0$, (c) H_1, $j = j_c(H_1)$, and (d) H_2, $j = j_c(H_2)$ while (e) shows the related critical current density $j_c(H)/j_c(0)$ versus H/H_1. The superconductor size is $20\times 20\xi(0)^2$ and the hole edge is $1{,}5\xi(0)$. The directions of super current densities are indicated by white arrow encircling the holes. The subscript of letter S is used to indicate the edges of a hole 0, 1, $1{,}5$, and 2.

perpendicular magnetic field. The electric voltage is calculated through $V(t) = \int \langle -\partial A_x(x,y,t)/\partial t \rangle dx$. Here the value of $\langle \partial A(x,y,t)/\partial t \rangle$ is taken as an average of the electric field over $-L/2 \le y \le L/2$ where L is the width of the superconductor. By observing the value $|\Psi(x,y,t)|$ and $V(t)$ we can observe whether the current reaching the critical condition. We use a type II superconductor having $\kappa = 2$. The mesh size of the superconductor is $0.5\xi(0)$, so that the calculation was done in N^2 meshes array while N is the number of meshes related to the size of superconductor. To observe the existence of the matching magnetic field on superconductor having an array of hole and the related critical current, we use the superconductor having size $20\times 20\xi(0)^2$.

III. RESULT AND DISCUSSION

The condition of minimum vortices criterion can be seen at Fig. 1. The vortices configuration remains the same as time grows and the electric voltage produced by the vortices motion remains the constant as time increases. This condition usually is obtained after 100000 steps. We use time step $\Delta t = 0{,}015$ in dimensionless unit to ensure the calculation stability. Using this criterion, we can determine the critical current at a certain magnetic field. It is found that the first matching magnetic field clearly exist at $H_1 = 0{,}4$ in which all vortices are pinned at the holes. At $H_2 = 2H_1$ all vortices are pinned at holes as well as at the lattice edges. The existence of the matching field is shown using $|\Psi(x,y)|$ contour at Fig. 2 (a) and (b). At critical current under matching magnetic fields value of $j_c(0)$, $j_c(H_1)$ and $j_c(H_2)$ can be seen from Tabel 1. It can be noticed that the enhancement factor due to hole array addition depend also on the size of hole. Here we observe that the values matching fields are $H_1 = 0{,}45$ and $H_2 = 0{,}83$ for S_2 sample and $H_1 = 0{,}45$ and $H_2 = 0{,}85$ for S_1 and $S_{1.5}$. The different value of H_1 and H_2 is caused by the size effect of hole size. Basically, matching magnetic fields exist and a lattice hole act as a strong vortices pinning. Further investigation on the effect of hole arrays done experimentally revealed that the enhancement factor depended on the number of holes, the lattice hole geometry as well as the hole sizes (Raedt et.al., 2004). These phenomena were already observed by other author (Silhanek et.al. 2005). When a line-holes is added to superconductor there is no such commensurate effect observed. Instead, the vortices pin at line hole at low magnetic field and they pin at both line holes and at inter line space. At the interline space the vortices experience a stronger

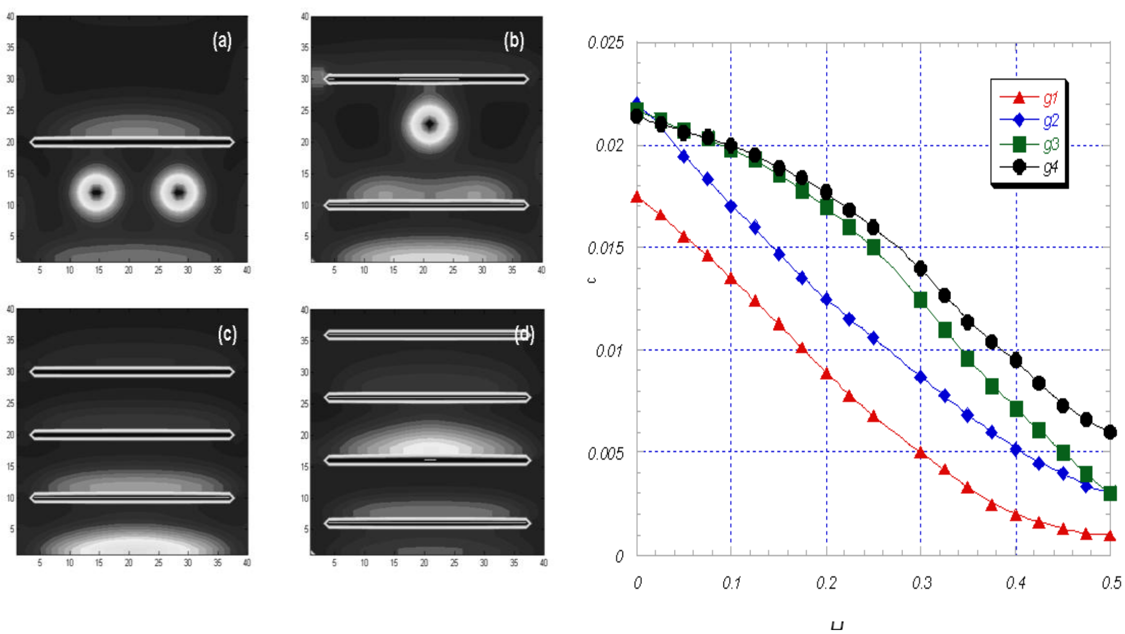

Figure 3: The contour of $|\Psi|$ at critical magnetic field $j_c(0{,}2)$ for superconductor having line hole 1,2,3, and 4 as indicated by (a), (b), (c) ,(d) and the symbols g_1 to g_4 . The symbol g_0 stands for superconductor without line hole and (e) the related critical current densities j_c versus H .

(at $j_c(H_1)$ and $j_c(H_2)$), the hole arrays can still resists the vortices from motion. The $j_c(H)$ curves produced due to the addition of hole arrays is shown at Fig. 2 (e). Here $j_c(H)$ is the critical current at H and $j_c(0)$ is the critical current at $H = 0$.The absolute pinning force due to the interaction between vortices and the ???.

The $x-$edges of line-holes act as vortices barrier and the holes act as vortices trapping center. Through this mechanism vortices motion is resisted by the lines hole (Fig. 3). Since the lines hole does not form a unit lattice hole cell, therefore there is no such commensurate fields and peaks in j_c curves as observed at superconductor having a hole array.

Other interesting phenomena in superconductor having lines hole compared to the one having an array hole is that it may produce higher critical currents at magnetic fields region $0 \le H \le 0{,}5$ without peaks. The critical current of g_4 is much higher compared to the one without hole (g_0) and still higher than the critical current produced by $S_{1,5}$ at magnetic fields less than H_1 . Experimentally, perhaps the fabrication of lines hole on superconductor is interesting because it may be produced easier than the fabrication of an array of hole but it may produce a higher critical current. Using minimum vortices motion we obtain the critical current on superconductor having an array of hole similar with the result obtained by experiment (Silhanek et.al., 2005) as well as the result obtained using simulated annealing and molecular dynamics (Misko et. al., 2005). Table 1 shows also the value of the critical current densities of the superconductor having lines hole. Although the addition of lines hole to the superconductor can be used to increase the critical current in wider magnetic range compare to the addition of an array of hole, unfortunately, so far there has been no experiment done in determining the critical current on a superconductor using such holes.

IV. CONCLUSION

The method of increasing the critical current of superconductor using holes addition is studied using time dependent Ginzburg-Landau equation. The calculation result of the critical current densities on the superconductor having an array of hole indicates the similarity with the result obtained by experiment. Although the curves of critical current on superconductor having line holes under magnetic field without peaks, the addition of lines hole to superconductor can enhance the critical current density wide range of magnetic field and produce the enhancement factors which are comparable with the ones produced by superconductor an array of hole.

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