Estimation of Electricity Storage Density of Compact SMESs Composed of Si-wafer Stacks Loaded with Superconducting Thin Film Coils in Spiral Trenches under the Constraints of the Critical Magnetic Flux Density

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Abstract. Numerical estimations of electricity storage volume density: \( W \) for a proposed compact superconducting magnetic energy storage system composed of 4 stacks of 20 to 1800 Si-wafers loaded with superconducting \( \text{YBa}_2\text{Cu}_3\text{O}_7-\delta \) thin film coils in spiral trenches formed by MEMS process were performed in conjunction with estimations of magnetic flux density and electromagnetic hoop stress applied to the coil. Changing the design parameters such as trench depth, trench width, trench wall thickness, number of stacked Si wafers, the inner-radius of the spiral coil under the fixed outer-radius of 47.45 mm, the maximum \( W \) was obtained to be 13.6 Wh/ℓ under the constraint of the maximum magnetic flux density applied to the coil: \( B_{\text{max}} < 20 \) T. The maximum hoop stress applied to the coil was estimated to be much lower than the mechanical strength limit of the Si wafer: 4 GPa, indicating that other substrate materials such as typical engineering ceramics can be used in place of Si wafer if microfabrication of spiral trenches is feasible.

1. Introduction
We have been developing a superconducting thin film coil in a spiral trench on a Si wafer for compact superconducting magnetic energy storage (SMES) as shown in figure 1. The thin film coil is embedded in the spiral trench in order to prevent it from coming off from the substrate by the electromagnetic stress: \( S \) applied to the coil. Because \( S \) is a hoop stress put upon the outer wall of the trench, the superconducting current must be reduced to keep \( S \) lower than 1/3 of the mechanical strength limit of the Si wafer \( \sigma_{\text{Si}} \): 4 GPa. Here, 1/3 is a safety factor. A proof of concept has been performed on a single Si wafer using NbN thin films showing energy storage of 0.01 mJ [1]. Increasing NbN thickness by mitigating film stress [2], the stored energy increased up to 0.1 mJ [3]. In a typical favourable design, multiple Si wafers which are engraved with a spiral coil (hereafter, we call it a wafer-coil for simplicity) are stacked to form a cylindrical unit as shown in figure 1(b), and the four units are combined to form a typical favourable minimum system as shown in figure 1(e). In this system, the electricity storage volume density: \( W \) was estimated to be 3.6 Wh/ℓ. The largest \( S \) near
the central axis of the coil unit: $S_{\text{max}}$ estimated from the magnetic flux density: $B$ along the central axis of a single-layer solenoid was 0.11 GPa which was well below $\sigma_{\text{Si}}/3$. For further improvement, we moved on to replacement of NbN by YBa$_2$Cu$_3$O$_7$-$\delta$ (hearafter, abbreviated as Y123) [4]. This replacement is to enable use of liquid hydrogen: 20.3 K or even of liquid nitrogen: 77K as a refrigerant instead of a cryogenic refrigerator to cool down below 13 K in the case of NbN. Even if we keep using a 4 K cryogenic refrigerator, another benefit of this replacement is that the critical superconducting current density $j_0$ of Y123 can be about $2 \times 10^{10}$ A/m$^2$ which is about 18 times larger than that of NbN [5]. Because $W$ is proportional to the square of the current, we may expect $18 \times 18 = 324$ times larger $W$ in the case of Y123 in comparison to that in the case of NbN, that is 1231 Wh/ℓ. Here, it should be noted that the $S$ becomes also 324 times larger, that is, 35.6 GPa by the replacement of NbN by Y123. Because the innermost portion of the spiral coil is not on the central axis of the coil, this value may be overestimated in some degree. However, 35.6 GPa is too large in comparison with $\sigma_{\text{Si}}/3$: 1.33 GPa. This means the maximum superconducting current in the coil must be much reduced from the value derived from $j_0$, and 1231 Wh/ℓ is not attained in reality. We intuitively know that we can mitigate this large $B$ and $S$ applied to the innermost portion of the coil by making its innermost diameter: $R$ larger, leaving the central part of the wafer uncovered with trenches. However, we lose $W$ again, simultaneously. Therefore, we must estimate how much we could mitigate $S$ and how much we lose $W$ quantitatively in concrete designs of the wafer-coils. In addition to $\sigma_{\text{Si}}$ against $S$, $B$ also has an upper limit to keep superconductivity, that is, critical magnetic flux density: $B_0$. In this paper, we report more precise estimations of $B$, $S$ and $W$ for more concrete designs of the stack of the wafer-coils.

2. Method of estimation

2.1. Inductance

Figure 2 schematically illustrates an approximately one-half of the cross-section of a wafer-coil showing principal design parameters of the spiral trench. Here, $R_{\text{wafer}}$ and $t$ stand for the radius and
thickness of the Si wafer, respectively. $R$ and $R_{\text{max}}$ stand for the radii of the inner wall of the innermost coil and the outer wall of the outermost coil, respectively. Parameters $d$, $z$, and $s$, stand for the trench width, the trench depth, and the trench wall thickness, respectively. Figure 3 shows a schematic of a stack of Si wafer-coils. The spiral coils on adjacent Si wafers are supposed to be connected through two through-holes formed in the wafers as frequently used in the conventional multi-layer interconnection technology [1]. Thus, the $m$ wafers illustrated in figure 3 are supposed to be series connected. For simplicity of calculation of inductance: $L$, this series-connected coils were simulated to be a single layer solenoid of the length $l$ which was equal to the height of the stack of $m$ Si wafer-coils and of the radius: $a R_{\text{max}} + (1 - \alpha) R$, where $|\alpha| \leq 1$. Because the portion of the spiral coil with larger diameter contributes more to $L$ than that with smaller diameter, $\alpha$ should be larger than 0.5 in reality. However, here, $\alpha$ was set to be 0.5 for simplicity. If the number of turns of the coil in a wafer is $n$, $L$ can be expressed using the formula of the single layer solenoid as follows:

$$L = K \cdot 4 \pi \times 10^{-7} \cdot \mu_r \cdot \pi \left( \frac{R_{\text{max}} + R}{2} \right)^2 \cdot \frac{(n m)^2}{l}$$

(1)

where $K$ is the Nagaoka's coefficient which is a function of $(R_{\text{max}} + R) / 2 l$, $4 \pi \times 10^{-7}$ is the magnetic permeability of free space, $\mu_r$ stands for relative magnetic permeability. In the case of Si, it is reasonable to set $\mu_r = 1$. Electric energy stored in this solenoid: $E$ can be expressed as $E = L I^2 / 2$. Here, superconducting current: $I$ flowing in the coil can be expressed as $I = d' \sqrt{j_0}$. Here, $W$ is calculated for the volume of cuboid including 4 stacks as shown in figure 1(e). Because the volume of the cuboid in figure 1(c) is $a \times a \times l$ including the space for refrigerant, magnetic shields and heat insulation, $W = (L - h / 2) \times 4 / (a \times a \times l)$. The length of solenoid: $l$ can be expressed as $l = m \cdot t$ using the number of Si wafer-coils stacked: $m$. In this paper, estimations of $W$ were performed in a case of $a = 0.3$ m and $t = 0.5$ mm. The value $n$ can be expressed as $n = (R_{\text{max}} + s - R) / (d + s)$. Because $s / R_{\text{max}} \ll 1$ and $s / R \ll 1$, $n$ can be approximated as follows:

$$n = \frac{R_{\text{max}} - R}{d + s}$$

(2)

Then, (1) can be expressed as follows:
\[ L = K \cdot 4\pi \times 10^{-7} \cdot \pi \left( \frac{R_{\text{max}} + R}{2} \right)^2 \cdot \left( \frac{R_{\text{max}} - R - m}{m + t} \right)^2 \] \quad (3)

Then, \( W \) can be expressed and approximated as follows:

\[ W = \frac{1}{2} K \cdot 4\pi \times 10^{-7} \pi \left( \frac{R_{\text{max}} + R}{2} \right)^2 \cdot \left( \frac{R_{\text{max}} - R - m}{m + t} \right)^2 \frac{x}{d \times z \times j_0} \approx \frac{1}{2} K \cdot 4\pi \times 10^{-7} R_{\text{max}}^4 \left( 1 - \frac{R^2}{R_{\text{max}}^2} \right)^2 \frac{x}{d \times z \times j_0} \times 4 \] \quad (4)

Because trenches cannot be formed on the peripheral ring area of the Si wafer of the width of at least 3 mm for handling wafer in the series of processes, \( R_{\text{max}} \) can be set in the limited range and is essentially constant. Therefore, \( W \) increases with decreasing \( R \). Equation (4) also teaches that \( W \) increases with decreasing \((s/d)\) and with increasing \( z \). Because \( K \) increases with \( l \), \( W \) also increases with \( l \). Although \( m \) does not appear in (4), \( W \) decreases with decreasing \( m \) because of decrease in \( K \).

2.2. Magnetic flux density

As for the calculation of the distribution of \( B \) generated by the wafer-coil, we replaced the spiral coil by concentric circular currents with the same \( R_{\text{max}}, R, d, s, \) and \( z \) for a calculation model. The calculation based on the Biot-Savart low was performed integrating \( j_0 \) in the \( d \times z \) rectangular cross-section of the trench using “integ.tplquad” function in a Python 3.6 calculation code. The calculation code also summed up the values of \( B \) at the innermost portion of the coil on a wafer caused by all the concentric circular currents on the same wafer and summed up the contributions of all the other wafers in a stack [6]. Figure 4(a) schematically illustrates the component of the magnetic flux density \( B \)

![Figure 4(a)](image)

**Figure 4(a)** Schematic geometry in estimation of the component \( B \) normal to the wafer at the radius \( R \) on a wafer caused by another wafer-coil at a distance \( D \) in the same stack and \( S \) caused by \( B \) and \( I \) in the coil, (b) dependence of \( B \) on \( D \) in the same stack and \( S \) caused by \( B \) and \( I \) in the coil, (c) variation of \( B_{\text{total}} \), the sum of the contributions of all the wafers in a stack to \( B \), as a function of the position of the wafer in the stack in a typical case of \( l = 30 \) cm where \( t = 0.5 \) mm and \( m = 600 \).
normal to the wafer at the innermost portion of the spiral coil at the radius $R$ on a wafer caused by another wafer-coil at a distance $D$ in the same stack. Figure 4(b) shows the dependence of the magnetic flux density $B$ on $D$ when $R_{\text{max}} = 45.8$ mm, $R = 22.0$ mm, $d = 0.025$ mm, $s = 0.01$ mm, $z = 0.3$ mm, $t = 0.5$ mm as in the illustration inserted topside. Because $B$ is plotted in logarithmic scale, it is clearly shown that $B$ decreases rapidly with increase in $|D|$, and is lower than 10% of the peak value in the region $|D| > 2.5$ cm. The total magnetic flux density $B_{\text{total}}$ is the sum of the contributions of all the wafers in a stack. Figure 4(c) displays a variation of $B_{\text{total}}$ as a function of the position of the wafer in the stack in a typical case of $l = 30$ cm where $t = 0.5$ mm and $m = 600$. At the position at $-15$ cm or $+15$ cm, the $B_{\text{total}}$ is lower than that at the central position: 0 cm. This can be intuitively understood from the summed areas painted in green in the inserts of minified figure 4(b) in figure 4(c). The $B_{\text{total}}$ takes the maximum value $B_{\text{max}}$ at the central position of the stack where the contributions of different wafers is summed up in the region: $|D| \leq l/2$.

2.3. Electromagnetic hoop stress

Expressing free electron density as $\rho \ m^{-3}$ and elementary charge: $1.60 \times 10^{-7} \ C$ as $e$, the charge: $q \ C$ in the superconducting film per length $dx$ along the trench can be expressed as $q = e \rho \ d \ z \ dx$. Expressing the electron velocity as $v$, $I$ is expressed as $I = e \rho \ d \ z \ v$. The Lorenz force $F$ imposed on the current $I$ can be expressed as $F = q \ v \ B = I d x \ B_{\text{total}}$. Because the corresponding surface area on the trench wall is $z \ dx$, the hoop stress $S$ in the unit of GPa on the trench wall can be expressed as follows:

$$S = I \ d x \ B_{\text{total}} / (z \ d x) \times 10^9 = I B_{\text{total}} / z \times 10^9$$

(5)

Because $S$ is normal to $B$ and $I$, $S$ gives hoop stress as shown in figure 4(a). When $B_{\text{total}}$ is $B_{\text{max}}$, $S$ is expressed as $S_{\text{max}}$, hereafter.

3. Results of estimations

3.1. Features of the system

To begin with, estimations in typical 4 designs of $d$ and $s$ in the case of $R_{\text{max}} = 47.45$ mm, $R = 45.4$ mm, $z = 0.3$ mm were performed to elucidate the features of the system described in equations (1)-(5). Table 1 displays the results of the estimations of $B_{\text{max}}$, $S_{\text{max}}$ and $W$ together with $n$ and $L$ for Designs (A)-(D). In Design (A), $B_{\text{max}}$ was approximately 20.7 T which was near $B_0$ (20 T) parallel with $c$-axis of Y123 at 79 K based on previously reported data [7]. $S_{\text{max}}$ was well below $\sigma_{0}/3$: 1.33 GPa. $W$ was 13.1 Wh/ℓ. In Design (B) and Design (C), the value of $d$ and $s$ were twice and quadruple of those in Design (A), respectively. Accordingly, in the cases of Design (B) and Design (C), the values of $n$ was a half and a quarter of that in Design (A), respectively, as derived from equation (2). Then $L$ in Design (B) and Design (C) were a quarter and one sixteenth of $L$ in Design (A), respectively, as derived from equation (1). In every 0.3 mm along the radial direction in Design (C), there is a current $I = d \ z \ j_0$ because one trench exists in average in every 0.3 mm. The current is the same in Design (B) because 2 trenches exist in average in every 0.3 mm. The current is also the same in Design (A) because 4 trenches exist in average in every 0.3 mm along the radial direction. This is the reason why the values of $B_{\text{max}}$ obtained through the process described in subsection 2.2 were estimated to be the same within calculation errors in Designs (A)-(C). However, the difference in the current per one trench made the difference in the values for $S_{\text{max}}$ in Designs (A)-(C) as derived from equation (5). In Designs (B) and

| Design | $d$ (mm) | $s$ (mm) | $n$ | $L$ (H) | $B_{\text{max}}$ (T) | $S_{\text{max}}$ (GPa) | $W$ (Wh/ℓ) |
|-------|---------|---------|-----|--------|--------------------|----------------------|-----------|
| (A)   | 0.05    | 0.025   | 28  | 7.07   | 20.7               | 0.0207               | 13.1      |
| (B)   | 0.1     | 0.05    | 14  | 1.77   | 20.8               | 0.0416               | 13.1      |
| (C)   | 0.2     | 0.1     | 7   | 0.44   | 20.8               | 0.0833               | 13        |
| (D)   | 0.05    | 0.1     | 14  | 1.76   | 10.4               | 0.0104               | 3.27      |
(C), the values of $W$ were the same as that in Design (A) in accordance with equation (4) because of the same value of $s/d$. Because the values of $d+s$ were the same both in Design (B) and (D), the values of $n$ and $L$ were also the same in Designs (B) and (D) within calculation errors. However, $B_{\text{max}}, S_{\text{max}},$ and $W$ in Design (D) was half, quarter, and quarter of $B_{\text{max}}, S_{\text{max}},$ and $W$ in Design (B) because the average current per $d+s$ along the radial direction in Design (D) was half of that in Design (B).

3.2. $B_{\text{max}} (T), S_{\text{max}} (\text{GPa})$ and $W (\text{Wh/l})$ as a function of $R$ under the fixed $R_{\text{max}}$ of 47.45 mm

We studied how we can mitigate $B_{\text{max}} (T)$ and $S_{\text{max}} (\text{GPa})$ applied to the innermost portion of the coil by increasing $R$, as well as how we lose $W (\text{Wh/l})$, simultaneously.

3.2.1. Dependence on the trench depth

Figures 5 show the variations of $B_{\text{max}}, S_{\text{max}}$ and $W$ as a function of $R$ under the fixed $R_{\text{max}}$ of 47.45 mm, $d$ of 0.1 mm, $s$ of 0.05 mm and $m$ of 600 in the cases of 4 different values of $z$: (a) 300 μm, (b) 30 μm, (c) 20 μm and (d) 15 μm. The numbers 1, 8, 10, …290 stand for $n$ for each estimated point. In all cases of (a)-(d), $B_{\text{max}}, S_{\text{max}}$ and $W$ decreased with $R$ gradually when $R$ was small, and steeply when $R$ approached $R_{\text{max}}$. $S_{\text{max}}$ was always well below $\sigma_{\text{Si}} / 3$. If we limited $B_{\text{max}}$ lower than $B_0$ in parallel with c-axis of Y123: 20 T as indicated with red horizontal lines in the figures 5(a)-(d), $R$ was decided to be (a) 45.5 mm, (b) 27.3 mm, (c) 17.5 mm, and (d) 7.6 mm, respectively as indicated vertical broken lines in the figures. In these 4 values of $R$, $W$ took values of (a) 12.3 Wh/t, (b) 8.1 Wh/t, (c) 6.0 Wh/t and (d) 4.3 Wh/t, respectively as indicated with blue horizontal lines in the figures. Figure 6 summarizes the variations of estimated $R$ value and corresponding $W$ value as a function of $z$ under the constraint of $B_{\text{max}} < 20$ T. Values of $R$ and $W$ increased with $z$ rapidly when $z$ is small, but saturated over $z > 0.1$ mm. The saturated values of $R$ and $W$ were approximately 45.5 mm and 12.3 Wh/t. Only a small area between $R=45.5$ mm and $R_{\text{max}} = 47.45$ mm on the wafer was to be covered with the spiral trench.

3.2.2. Dependence on the number of stacked wafer-coils

Figures 7 show the variations of $B_{\text{max}}, S_{\text{max}}$ and $W$ as a function of $R$ under the fixed $R_{\text{max}}$ of 47.45 mm, $d$ of 0.1 mm, $s$ of 0.05 mm and $z$ of 0.3 mm in the cases of 6 different values of $m$: (a) 20, (b) 60, (c) 100, (d) 200, (e) 600, (f) 1200. If we limited $B_{\text{max}}$ lower than $B_0$ in parallel with c-axis of Y123: 20 T
Figure 6 Estimated $R$ value and corresponding $W$ value as a function of $z$ under the constraint of $B_{\text{max}} < 20$ T.

Figure 7 Calculated results of $B_{\text{max}}$ (T), $S_{\text{max}}$ (GPa) and $W$ (Wh/ℓ) as a function of $R$ under the fixed $R_{\text{max}}$ of 47.45 mm, $d$ of 0.1 mm, $s$ of 0.05 mm and $z$ of 0.3 mm in the cases of 6 different values of $m$: (a) 20, (b) 60, (c) 100, (d) 200, (e) 600 and (f) 1200.

again as indicated with red horizontal lines in the figures 7(a)-(f), $R$ was desired to be (a) 43.2 mm, (b) 44.4 mm, (c) 44.8 mm, (d) 45.2 mm, (e) 45.5 and (f) 45.5, respectively as indicated vertical broken lines in the figures. $W$ took values of (a) 13.0 Wh/ℓ, (b) 13.2 Wh/ℓ, (c) 13.6 Wh/ℓ and (d) 13.2 Wh/ℓ, (e) 12.3 Wh/ℓ and (f) 12.4 Wh/ℓ, respectively as indicated with blue horizontal lines in the figures.

Figure 8 summarizes the variations of estimated $R$ value and corresponding $W$ value together with $K$ value as a function of $m$ under the constraint of $B_{\text{max}} < 20$ T. Values of $R$ and $K$ increased with $m$ while $W$ were almost constant between 12 and 14 Wh/ℓ. As shown in figure 4(b), wafer-coils at distances more than 2.5 cm do not significantly contribute $B_{\text{max}}$ which means increase in $m$ beyond 100 does not
request a significant increase in $R$ to keep $B_{\text{max}}$ below 20T. When $m < 100$, the loss in $W$ caused by decrease in $K$ was to be compensated by the decrease in the volume: $a \times a \times m \times t$. When $m > 100$, the gain in $L$ caused by increase in $m$ was compensated by the increase in the volume: $a \times a \times m \times t$ to keep the value of $W$ approximately constant. The maximum value of $W$ was approximately 13.6 Wh/ℓ.

4. Discussion

According to the estimated results presented in figures 5-8, the maximum $W$ of 13.6 Wh/ℓ is to be attained in the conditions $z = 0.3$ mm, $m = 100$, $R = 44.8$ mm, $R_{\text{max}} = 47.45$ mm, $d = 0.1$ mm and $s = 0.05$ mm under the constraint of $B_{\text{max}} < 20$ T. As we learned from the results presented in table 1, a change of the trench size from the present ($d = 0.1$ mm, $s = 0.05$ mm) to ($d = 0.05$ mm, $s = 0.025$ mm) or to ($d = 0.01$ mm, $s = 0.005$ mm) will give the same value of $W$. In this case, only the peripheral region of the Si wafer is covered by the spiral coil because $R = 44.8$ mm. If we changed $z$ from 0.3 to 0.02 mm, it becomes much easier to fill the trench by sputter-deposition of Y123 and by electroplating of Cu. According to the results shown in figure 6, the relatively large area had to be covered by the spiral coil because $R = 17.5$ mm in this case. However, we lose $W$ value significantly from 13.6 Wh/ℓ to 6.5 Wh/ℓ. Here, it should be noted that $W$ was calculated using the volume of cuboid including 4 stacks as shown in figure 1(e). In practical instrumentation, volumes for a cryogenic refrigerator should be taken into consideration. The present estimation which used $B_0=20$ T based on the data for epitaxially grown single crystal 30μm thick film [7] gives the prospect of the proposed system and motivation of the ongoing experimental development of c-axis oriented Y123 film on Si wafer with appropriate buffer layers for high $B_0$ [4]. Through all the estimations, the values of $S_{\text{max}}$ were less than 0.5 GPa which was much lower than $\sigma_{\text{Si}}/3$. This fact indicates that other substrate materials such as typical engineering ceramics can be used in place of Si wafer if microfabrication of spiral trenches is feasible. This may open the door to other applications of the present wafer-coils besides SMES, such as, for example, magnetic resonators for wireless power transfer systems with a longer transfer range utilizing the high-quality factor of superconducting coils [8].

5. Conclusion

Estimations of $B_{\text{max}}$, $S_{\text{max}}$, and $W$ for a proposed compact SMES system were performed. Changing the design parameters $z$, $m$, $d$, $s$, $R$, the maximum $W$ was obtained to be 13.6 Wh/ℓ under the constraint of $B_{\text{max}} < 20$ T. The hoop stress was estimated to be much lower than $\sigma_{\text{Si}}/3$, which indicates that other substrate materials such as typical engineering ceramics can be used in place of Si wafers if microfabrication of spiral trenches is feasible.

Figure 8 Estimated $R$ value and corresponding $W$ value as a function of $m$ under the constraint of $B_{\text{max}} < 20$ T.
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