A possibility of enhancing $J_c$ in MgB$_2$ film grown on metallic hastelloy tape with the use of SiC buffer layer

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Abstract

We have grown MgB$_2$ on SiC buffer layer by using metallic Hastelloy tape as the substrate. Hastelloy tape was chosen for its potential practical applications, mainly in the power cable industry. SiC buffer layers were deposited on Hastelloy tapes at 400, 500, and 600 °C by using a pulsed laser deposition method, and then by using a hybrid physical-chemical vapor deposition technique, MgB$_2$ films were grown on the three different SiC buffer layers. An enhancement of critical current density values were noticed in the MgB$_2$ films on SiC/Hastelloy deposited at 500 and 600 °C. From the surface analysis, smaller and denser grains of MgB$_2$ tapes are likely to cause this enhancement. This result infers that the addition of SiC buffer layers may contribute to the improvement of superconducting properties of MgB$_2$ tapes.

Keywords: MgB$_2$ films, critical current density, SiC buffer layers, Hastelloy

1. INTRODUCTION

More than a decade ago, a simple binary boride, MgB$_2$, had been discovered to be a superconducting compound with a $T_c \approx 39$ K [1], one of the highest transition temperatures observed for any non-cuprate material. A great number of experimental and theoretical investigations have been subjected to MgB$_2$ [2-5], not only to understand its superconducting mechanism, but also to explore its future prospect, especially in the power cable industry.

It has been widely known that SiC doping is one of the effective methods to improve the superconducting properties of MgB$_2$ [6-8]. In our current work, we are applying SiC in a slightly different form; a form of buffer layer. The usage of amorphous SiC impurity layers had also proven to improve the critical current density ($J_c$) values of MgB$_2$ films [9]. Furthermore, based on our previous works [10-11], MgB$_2$ films with crystalline SiC buffer layers deposited on Al$_2$O$_3$ substrates have been confirmed to enhance $J_c$ values.

In order to be able to be manufactured in a larger scale, more applicable metallic substrates are required to produce high-quality MgB$_2$ superconductors. Wide variety of metallic substrates has been applied in the making of MgB$_2$ superconducting tapes throughout the years [12-14]. All of which were made without inserting any buffer layer. However, the $J_c$ values of these different substrates-MgB$_2$ films are not fairly high. For this reason, we have been investigating the usage of SiC buffer layer deposited on metal Hastelloy tape as the substrate in MgB$_2$ film. Hastelloy itself has been noted to have several advantages, such as highly flexible, low corrosive and low AC loss-material [15]. And as for SiC buffer layer, its presence is highly anticipated to overcome several potential issues that might occur if we use Hastelloy tape as the substrate. Preventing metal diffusion that could penetrate the MgB$_2$ films, supplying the carbon which may be needed to enhance $J_c$; are some of the SiC buffer layers expected roles in fabricating MgB$_2$ tapes.

 Principally, this preliminary work was conducted based on our belief that SiC buffer layer plays a significant part in improving MgB$_2$ superconducting properties when SiC buffer layers placed on the Al$_2$O$_3$ substrate. And since the effect of SiC/Hastelloy on MgB$_2$ tapes has not extensively exposed, there are possibilities of getting interesting results on the superconducting properties of MgB$_2$ films when SiC is applied on the metal Hastelloy.

This study on SiC buffer layers is essential to accommodate basic knowledge on the feasibility of SiC/Hastelloy structure to improve the $J_c$ values of MgB$_2$ tapes. Hopefully, by introducing metallic Hastelloy tape as the substrate for SiC buffer layer, there are much room for improvement for the production of better-quality of MgB$_2$ tapes in the near future.

2. EXPERIMENTS

The substrate used for SiC buffer layer fabrication in this work was metallic Hastelloy tape. A typical pulsed laser deposition process involved heating the substrate to 400, 500, and 600 °C, and keeping it at these temperatures for 10 min by means of pulsed laser deposition (PLD) which then
created a thickness of less than 200 nm. The deposition was conducted inside the vacuum chamber of ~10^{-6} Torr. Laser beams were generated from a KrF excimer laser (\(\lambda = 248\) nm) and the laser energy was set at 230 mJ with a repetition rate of 8 Hz.

MgB\(_2\) thin films were fabricated inside a hybrid physical-chemical vapor deposition (HPCVD) system. The SiC/Hastelloy tapes were then heated up to 550 °C in 100 Torr of H\(_2\) gas flow for 15 minutes. As for the pure MgB\(_2\), bare Hastelloy tape was used as the substrate. B\(_2\)H\(_6\) : H\(_2\) gas flow at 10 : 90 sccm was introduced into the quartz reactor to start the growth of MgB\(_2\) films. At last, the fabricated films were cooled down to room temperature in a flowing H\(_2\) carrier gas. As a result, the thickness of MgB\(_2\) films is less than 1 μm in average.

The surface morphology and the structure of the MgB\(_2\) films were investigated using scanning electron microscopy (SEM) and X-ray diffraction (XRD). The values of critical current density \(\mathcal{J}_c\) were carried out from the magnetization measurements obtained by using a magnetic property measurement system (MPMS).

**3. RESULTS AND DISCUSSIONS**

In Fig. 1, the XRD patterns (0-20 scans) for both pure MgB\(_2\) films grown on bare Hastelloy tape and MgB\(_2\) films deposited on SiC/Hastelloy buffer layers with three SiC deposition temperatures of 400, 500, and 600 °C are shown. The different temperatures are essential for crystalline SiC buffer layers to be properly grown on the Hastelloy substrates. This was also done in our previous works on MgB\(_2\)/SiC/Al\(_2\)O\(_3\) [10-11]. The crystalline SiC was formed as the temperature increased. However, SiC peaks are hard to detect by XRD alone; they inconsistently appear as minor peaks in some of SiC/Hastelloy samples of our other works. This may due to the reaction between SiC and Hastelloy which affected the structure of SiC buffer layers.

As can be seen in the figure, the MgB\(_2\) (101) peaks of MgB\(_2\)/SiC/Hastelloy films are becoming less intense, while pure MgB\(_2\) shows a slightly higher intensity of the peak. Other peaks appeared on the patterns are combination between MgB\(_4\) and Boron peaks with various axis orientations. This result is comparable with others’ reports on MgB\(_2\)/Hastelloy tapes which showed relatively small MgB\(_2\) (101), MgB\(_4\) and Boron peaks [16-18]. In Fig. 2. SEM images of pure MgB\(_2\) film and MgB\(_2\) films deposited at different temperatures on SiC/Hastelloy are presented. The grains of pure MgB\(_2\) in Fig. 2(d) seems to be bulkier than the other MgB\(_2\) films on SiC/Hastelloy. Whereas MgB\(_2\) films deposited on SiC/Hastelloy are showing smaller-leaner grains along with various orientations of the grains which are in conformity with the XRD results that showed all MgB\(_2\) samples have randomly oriented grains. These random-oriented grains are also found in our related works on MgB\(_2\)/SiC/Al\(_2\)O\(_3\) films [11]. At cross section area (not shown here), all MgB\(_2\) samples have approximately less than 1 μm thickness.

In addition, pure MgB\(_2\) film displayed a delaminating problem in which the quality of the film surface deteriorated to a point where the film had become relatively fragile to handle. However, that was not the case with MgB\(_2\)/SiC/Hastelloy films where all the samples are firmly attached at the surface. This implies that SiC somehow improve the quality of the surface and prevent the delaminating issue. It also gives us a hint that thicker MgB\(_2\) of more than 1 μm would solve the delaminating issue, and hence significantly upgrade the surface condition. In another on-going work, we have deposited a thicker MgB\(_2\) film on Hastelloy tape and the thicker MgB\(_2\) has been proven to stop the surface to be delaminated.

![Fig. 1. X-ray diffraction patterns of the MgB\(_2\) films with SiC buffer layers deposited on Hastelloy tape at temperatures of: (a) 400, (b) 500, (c) 600 °C, and (d) Pure MgB\(_2\), respectively. The peaks labeled with an asterisk arise from the Hastelloy tape substrate.](image1)

![Fig. 2. Plane SEM images for MgB\(_2\) films on Hastelloy tape with SiC buffer layers deposited at different temperatures of: (a) 400, (b) 500, (c) 600 °C, and (d) Pure MgB\(_2\) grown on bare Hastelloy tape.](image2)
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When compared with the \( J_c \) values from other MgB\(_2\)/Hastelloy tapes [16,18], it is apparent that our \( J_c \) has slightly lower values over the whole region. MgB\(_2\) thickness of less than 1 \( \mu \)m may be the cause of this low values. In the M-H curves (not shown here), MgB\(_2\)/SiC/Hastelloy films showed weak superconducting signals, thus at high field region, fluctuation increased. In our on-going work on MgB\(_2\)/SiC/Hastelloy, thick MgB\(_2\) films of more than 2 \( \mu \)m are proven to produce clear and stronger superconducting signals. Nevertheless, our MgB\(_2\) films have higher \( J_c \) values at zero fields than the ones of another report [17].

Even though the enhancement of \( J_c \) values of MgB\(_2\)/SiC/Hastelloy films are still lower than those of the MgB\(_2\) films grown on SiC/Al\(_2\)O\(_3\), as reported in our other related works [10,11]; still, this result indicates a positive signal of the possibility of enhancing \( J_c \) values of MgB\(_2\) films by using a SiC/Hastelloy structure.

4. CONCLUSION

SiC buffer layers on metallic Hastelloy tapes are likely to enhance the \( J_c \) values of MgB\(_2\) films. Enhancement of \( J_c \) may result from the alteration in microstructure, grain sizes, and grain orientations of MgB\(_2\)/SiC/Hastelloy films. However, more detailed analysis on the pinning source may provide better understanding on the cause of these \( J_c \) enhancements.

Our work emphasizes the importance of fabricating MgB\(_2\) films on SiC buffer layers with potential substrates, such as Hastelloy tape. This preliminary study, practically, provides a good start for more possibilities in fabricating better and more advanced MgB\(_2\)/SiC/Hastelloy films. It is our hope that this result would be an auspicious beginning for improving the superconducting properties of MgB\(_2\) tapes which would be a substantial breakthrough in the power cable applications.

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Fig. 3. Effect of SiC buffer layers on the field dependence of critical current density \( (J_c) \) curves measured at (a) 5 and (b) 20 K for pure and SiC-buffered-MgB\(_2\) films. MgB\(_2\) samples with SiC buffer layers grown on Hastelloy tape at 500 and 600 °C show larger \( J_c \) values than those of pure MgB\(_2\) at whole field region.

Another important parameter for practical applications of MgB\(_2\) is the critical current density \( (J_c) \). The values of \( J_c \) for pure MgB\(_2\) and MgB\(_2\)/SiC/Hastelloy films when subjected to an applied magnetic field are shown in Fig. 3. \( J_c \) values were obtained from the magnetization hysteresis loops (MHLs) using the Bean critical model [19].

The \( J_c-H \) behavior at both temperatures of 5 and 20 K has been improved with the addition of SiC buffer layers deposited at 500 and 600 °C, while pure MgB\(_2\) films show relatively lower \( J_c \) at the whole magnetic field region. MgB\(_2\) films on the SiC buffer layer deposited at 500 and 600 °C showed enhanced \( J_c \) values over the whole magnetic field region, despite the fluctuations of the \( J_c \) values which are mainly shown in the higher field region. This may be resulted from the slightly smaller grains size of MgB\(_2\) films on the SiC buffer layers when compared with the pure MgB\(_2\) film, as depicted in Fig. 2, which then created a stronger pinning source and hence the enhanced \( J_c \) values. On the other hand, the MgB\(_2\) film on SiC buffer layer deposited at 400 °C is not showing any enhancement most probably due to the low deposition temperature. This implies that the temperature above 400°C is most likely providing an optimum condition for SiC to be grown completely on the Hastelloy substrate. Additionally, bigger size of the grains of the pure MgB\(_2\) film might have generated less strong pinning sources which then contributed to the decreased \( J_c \) values.


