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Quench and recovery characteristics of second-generation high-temperature superconducting GdBCO coated conductor with various patterns of stabilizers

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A B S T R A C T

This paper investigates the quench and recovery characteristics of second-generation high-temperature superconducting GdBCO coated conductors (CC) with variously patterned stabilizers in over-current conditions. A chemical etching method was used to produce various patterns of stabilizer on GdBCO CC without degrading current-carrying capacity. From the results of the over-current testing of GdBCO CC tapes with variously patterned stabilizers, the tape that had stabilizer with longitudinally disconnected patterns exhibited higher voltage increase and slower recovery time than those that had continuity of stabilizers along the longitudinal direction, because the excessive heat and current could not be transferred through the stabilizers in the former. Overall, uniform heat and current distributions along the stabilizer of GdBCO CC are among the critical factors determining thermal and electrical stabilities of a GdBCO magnet in over-current conditions, especially when quench occurs.

Introduction

Since the advent of yttrium barium copper oxide (YBCO) superconductivity, second-generation (2G) high-temperature superconductivities (HTSs) of several rare-earth compositions have been discovered, which have been engineered for superconducting applications. Among various 2G HTSs, gadolinium (Gd)-based 2G HTS wire exhibits superior current-carrying capacity–perpendicular magnetic field properties compared to other rare-earth-based competitors; hence, many companies such as SuperPower Inc., SuNam Co. Ltd., and SuperOx are trying to produce km-class long-length wires for use in future 2G HTS applications such as cables, superconducting magnetic energy storage (SMES), rotating machines, nuclear magnetic resonance (NMR), and magnetic resonance imaging (MRI) [1–9]. However, prior to using the GdBCO conductor for practical superconducting applications, it is essential to thoroughly evaluate its thermal and electrical stabilities as it comprises multiple layers of metal compounds with nano-thickness, because a fault current may occur due to accidentally damaged electrical insulation, lightning striking an overhead line, or power failure, a situation particular to electrical power systems for smart grid applications. The subsequent fault current can exceed the nominal operating current of the GdBCO conductor, which may lead to a transition to the normal state (i.e., “quench”) of the superconductor, eventually resulting in irreversible damage to the conductor or even the entire power system [10]. Thus, many studies have examined the thermal/electrical characteristics of 2G HTS conductors in over-current conditions [11–14].

In general, commercial GdBCO conductors are produced as a combination of layers consisting of a substrate, buffer, GdBCO, stabilizer, and/or reinforcement. Among them, stabilizers such as copper, silver, and stainless steel play the role of bypassing the over-current and transferring the excessive heat in the event of a quench. Therefore, it is necessary to determine the appropriate material and design of the stabilizer, especially for fault current limiting performance [15–17].

In this study, the quench and recovery characteristics of GdBCO coated conductors with various patterned stabilizers were investigated through over-current tests. The purpose of the over-current test was to intentionally quench the GdBCO sample, thereby subjecting it to severe operating conditions over a short period of time and to thereby examine the thermal and electrical stabilities of the sample.

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Table 1
Specifications of the GdBCO coated conductor tape.

Parameters		Value
Model name		SuperPower, "SCS4050"
Stabilizer, Copper	[μm]	20 (on each side)
GdBCO	[μm]	~1
Buffer	[μm]	~0.085
Substrate, Hatelloy	[μm]	50

Experimental details

GdBCO coated conductor

Table 1 lists the specifications of the GdBCO coated conductor (CC) (SCS4050, SuperPower Inc.) used in this study. It was 4 mm wide and ~92 μm thick. Buffer layers (~0.1 μm) were deposited on a Hastelloy substrate layer (~50 μm) via ion beam assisted deposition (IBAD) using a magnetron sputtering system. The GdBCO superconducting layer (~1 μm) was deposited on the buffer layer by metal-organic chemical vapor deposition (MOCVD); an Ag stabilizer layer (~2 μm) was then sputtered on the GdBCO superconducting layer and the bottom of the substrate layer. Finally, the conductor was completely surrounded by a copper (Cu) stabilizer (20 μm) via the electroplating method.

Chemical etching process

A chemical etching method was employed to produce various patterns of stabilizer without serious degradation of current-carrying capacity. The etchant used for this process was Cu ETCH 49-1 (from Transene Co.). The total length of GdBCO tape sample used for this study was 7 cm. As shown in Fig. 1(a), Kapton tape was attached to the non-etched surface to protect the Cu stabilizer from unwanted etching. The etchant was diluted with distilled (DI) water (50% by weight) to moderate the etching reaction and achieve a homogeneously etched surface. Fig. 1(b) shows a photo and SEM images of the sample after chemical etching. As shown in Fig. 1(b), the Cu layer directly exposed to the etchant was completely removed without damaging the surface morphology of the GdBCO layer during the chemical etching process.

Preparation of GdBCO test samples with various patterned stabilizers

Fig. 2 shows schematic drawings of GdBCO test samples with variously patterned stabilizers. The exposed areas of samples 1, 2, 3, and 4 were all 1 cm^2 to provide identical conditions when over-current testing was performed.

Over-current tests

Sets of over-current tests were carried out at 77 K to examine the thermal/electrical characteristics of test samples with variously patterned stabilizers. Over-current pulse was applied to the sample in three steps: 1) an operating current (I_{op}) of 0.5 × I_c (at 77 K) for 10.5 s, 2) over-currents (I_{over}) for 100 ms, and 3) I_{op} again for a few seconds until the sample recovered.

Results and discussion

V-I characteristics

Fig. 3 shows the voltage versus current curves (*V-I* curves) for samples 1–4 with various stabilizer patterns and a sample without chemical etching. The critical current (I_c) values were measured in a bath of liquid nitrogen (LN_2, 77 K) using the criterion of 1 μV/cm. The I_c value of the bare sample was 103 A before chemical etching. After etching, the I_c values of samples 1–4 were 100, 99, 99, and 102 A, respectively. Compared to the bare sample, ~3.9% decrease in I_c was observed for samples 2 and 3. In general, there was no serious degradation in the superconducting properties of any of the samples, which implied that chemical etching is an appropriate method for designing the pattern of the stabilizer.

Over-current characteristics for GdBCO short samples 1–4

Fig. 4 shows $V(t)$ traces of samples 1–4 obtained from over-current (I_{over}) testing at I_{op} = 0.5 × I_c, I_{over} = 2.4 × I_c and 2.6 × I_c for 100 ms. As shown in Fig. 4(a), when I_{over} = 2.4 × I_c was applied for 100 ms, the voltage of sample 1 started increasing at ~10.52 s, gradually reaching 0.9 V at 10.6 s, and then decreasing to zero at 11.5 s. This implied that Joule heating was caused by the over-current pulse and it completely dissipated due to LN_2 cooling, resulting in the sample fully recovering to the superconducting state. The test results for samples 2 and 3 showed similar $V(t)$ traces to that of sample 1; however, their voltages reached zero at 12.2 and 12.3 s, respectively, which lagged behind that of sample 1 (11.5 s).

In the case of sample 4, the voltage did not reach 0 V until I_{op} was cut off, implying that the sample had not completely recovered. The maximum voltages of samples 1–4 at I_{over} = 2.4 × I_c were 0.91, 0.97, 1.01, and 3.14 V, respectively, which correspond to peak Joule heating fluxes (q_{peak}) of 109.2, 115.2, 119.9, and 384.3 W/cm^2, respectively, listed in Table 2. Note that, the q_{peak} is peak Joule heating flux at the maximum voltage. We assumed that the Joule heat generation occurs at the area between the voltage taps, and then it was simply calculated by the following equation:

$$q_{peak} = \frac{I_{op}^2 R}{A} [W/cm^2]$$

where I_{op} is the operating current, R is the resistance at the maximum voltage, and A is the area between voltage taps. From the test results, it is supposed that the highest q_{peak} of sample 4 is attributed to inefficient heat transfer through the Cu stabilizer in the longitudinal direction because of poor connection of the stabilizer, with the result that quench heat was accumulated locally in sample 4.

During testing at I_{over} = 2.6 × I_c (see Fig. 4(b)), the voltage increased and finally reached 1.2, 1.4, 1.5, and 3.4 V for samples 1–4, respectively, corresponding to q_{peak} values of 156.0, 193.1, 180.1, and 450.8 W/cm^2, respectively. As expected, the q_{peak} value increased with increasing I_{over}. Thereafter, the voltages of samples 1, 2, and 3 eventually decreased to 0 within ~2 s, while that of sample 4 did not reach zero until I_{op} was cut off due to discontinuity of the stabilizer in the longitudinal direction. These test results confirmed that samples 1–3 exhibited better stability than sample 4 due to the existence of longitudinal continuity of the stabilizer facilitating effective heat transfer in the event of a quench.

Over-current characteristics for multi-stacked GdBCO samples #1–3

Another set of over-current tests was carried out with respect to I_{over}, to investigate the quench and recovery characteristics of multi-layered GdBCO tapes. As shown in Fig. 5, 3 pieces of "*healthy*" samples 1, 2, and 3 used for the prior over-current tests were multi-stacked in parallel and both ends of each stacked sample were connected using PbSn solder. The I_c values of samples #1, #2, and #3 measured in a liquid nitrogen bath using the criterion of 1 μV/cm were almost identical at ~300 A.

Fig. 6 shows $V(t)$ traces of samples #1, #2, and #3 obtained during the over-current tests at I_{op} = 0.5 × I_c and I_{over} ranging from 700 to 800 A. When I_{over} = 700 A was applied to sample #1, the voltage started to increase at ~10.52 s, rapidly reached the maximum voltage (V_{max}) of 0.45 V at ~10.6 s, and then decreased to 0 at 11.37 s, which means that the recovery time (t_r) was 0.77 s. As expected, V_{max} and t_r increased with increasing I_{over}. The V_{max} of sample #1 at I_{over} = 725,

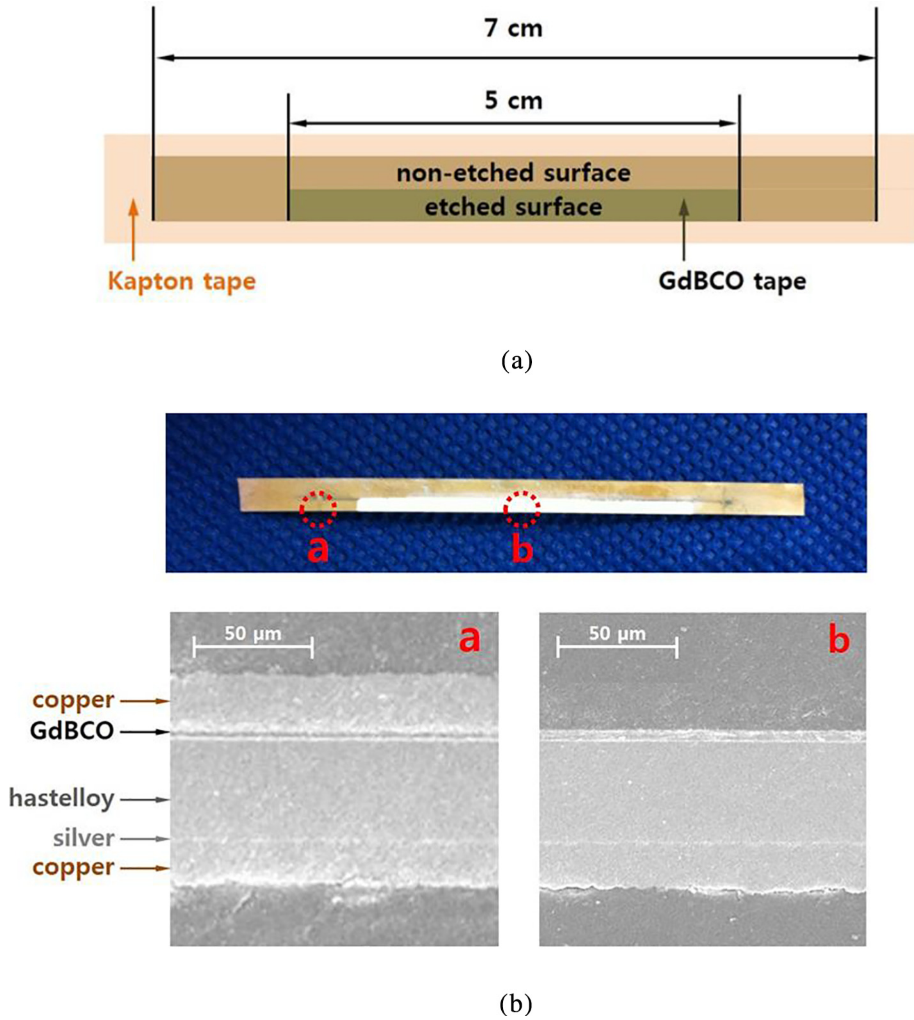

Fig. 1. A schematic drawing of the GdBCO CC tape (a), and a photo and SEM images (b) of the tape after chemical etching.

750, 775, and 800 A were 0.59, 0.68, 0.94, and 1.11 A, respectively and the t_r values were 0.88, 1.22, 1.92, and 2.82 s, respectively. The test results indicated that sample #1 had fully recovered to the superconducting state due to effective heat dissipation through stabilizers as well as cooling by LN_2.

In the case of sample #2, the V_{max} and t_r values obtained during testing at I_{over} = 700, 725, and 750 A were 0.49 V (t_r = 0.93 s), 0.64 V (t_r = 1.73 s), and 0.76 V (t_r = 2.45 s), respectively, which were higher than those obtained from the tests of sample #1. During further increase of I_{over} to 775 and 800 A, the voltages did not reach zero until I_{op} was cut off, indicating a "current-sharing" mode in which the stabilizer began to "share" the operating current. It is suggested that the energy from Joule heating could not be dissipated easily—in particular at the mid-placed piece—because natural convection of LN_2 rarely occurred due to the absence of a gap between the pieces at the top and bottom, unlike in the case of sample #1. Consequently, this led to inefficient

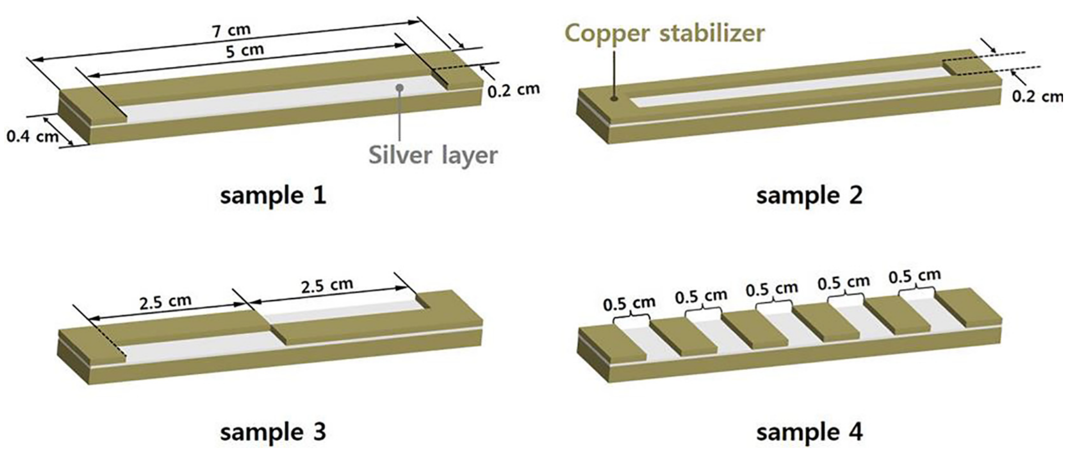

Fig. 2. The Schematic drawings of GdBCO test samples with various patterns of stabilizers.

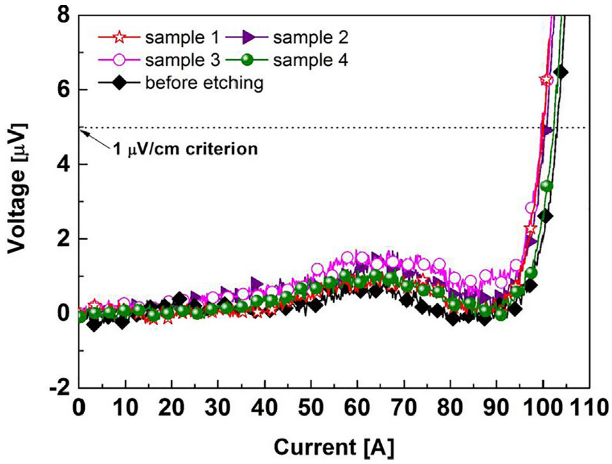

Fig. 3. *V-I* curves for samples 1–4 and a bare sample.

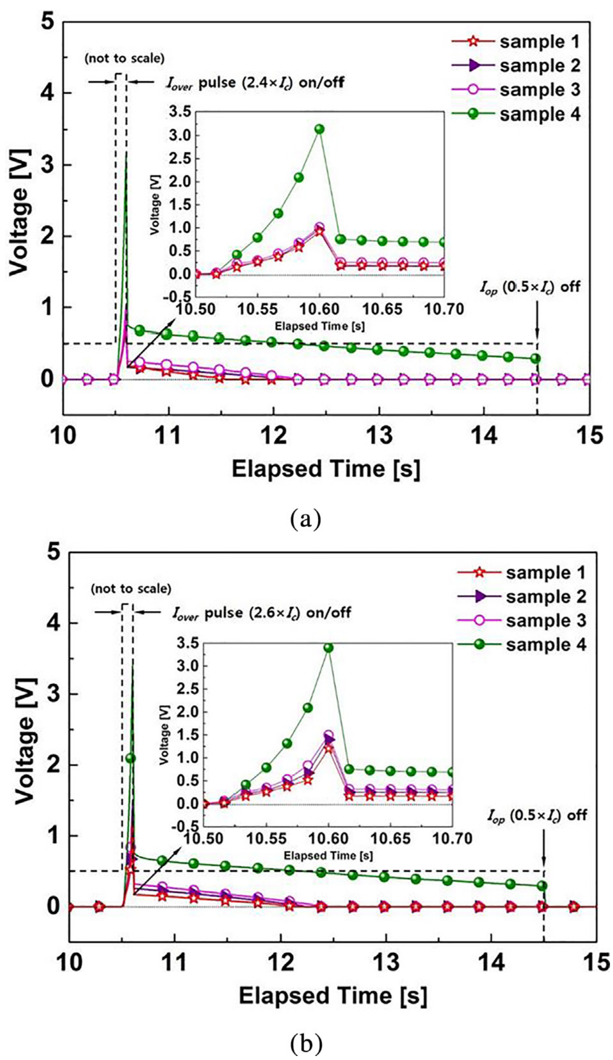

Fig. 4. Voltage traces of samples 1–4 obtained during over-current testing at I_{op} = 0.5 × I_c, I_{over} = 2.4 × I_c (a) and I_{over} = 2.6 × I_c (b) for 100 ms.

heat exchange between LN_2 and the mid-placed sample in which non-recovering resistive zones remained.

The test results of sample #3 at I_{over} = 700, 725, 750, and 775 A showed similar behaviors to those obtained from sample #2. The V_{max} and t_r values increased with increasing I_{over}. However, current-sharing was initially observed at I_{over} = 750 A, which is lower than that in the case of sample #2 (775 A). More importantly, when I_{over} = 800 A was applied, the voltage increased to 3.59 V at ~10.6 s, and then decreased to 0.72 V at 10.7 s. Thereafter, the voltage gradually increased again and it finally disappeared, which indicated that sample #3 had completely quenched. This implied that the energy from Joule heating was poorly dissipated because the excessive quench heat was not well-transferred through stabilizers in the longitudinal direction due to the existence of region "a" (see Fig. 5) to create a bottleneck and increase Joule heating locally. Therefore, uniform heat distribution along the multi-stacked GdBCO sample is one of the critical factors determining the thermal and electrical stabilities in the over-current condition.

Table 2
Calculated peak Joule heating fluxes of samples 1–4.

Peak Joule heating flux		sample 1	sample 2	sample 3	sample 4
q_{peak} at I_{over} = 2.4 × I_c	[W/cm^2]	109.2	115.2	119.9	384.3
q_{peak} at I_{over} = 2.6 × I_c	[W/cm^2]	156.0	180.1	193.1	450.8

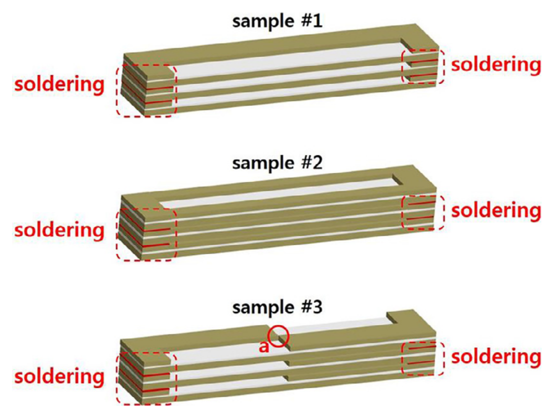

Fig. 5. Schematic drawings of multi-stacked GdBCO samples with various patterns of stabilizers.

Conclusion

This paper reports the quench and recovery characteristics of second-generation high-temperature superconducting GdBCO coated conductors (CCs) with various patterns of stabilizer. A chemical etching method was used to produce various patterns of stabilizer on the GdBCO CC without degrading the current-carrying capacity. The over-current test showed that the GdBCO CC tapes that had continuous stabilizer along the longitudinal direction exhibited better thermal and electrical stabilities than those having stabilizers with longitudinally disconnected patterns, because the longitudinal continuity of stabilizer facilitated effective heat and current transfers through the stabilizer in the event of a quench. Overall, uniform heat and current distributions along the stabilizer of GdBCO CC are among the most critical factors determining the thermal and electrical stabilities of a GdBCO magnet in over-current conditions. Further study on the simultaneous quench characteristics of GdBCO tapes with various stabilizers' patterns will be carried out for the practical use in SFCL applications.

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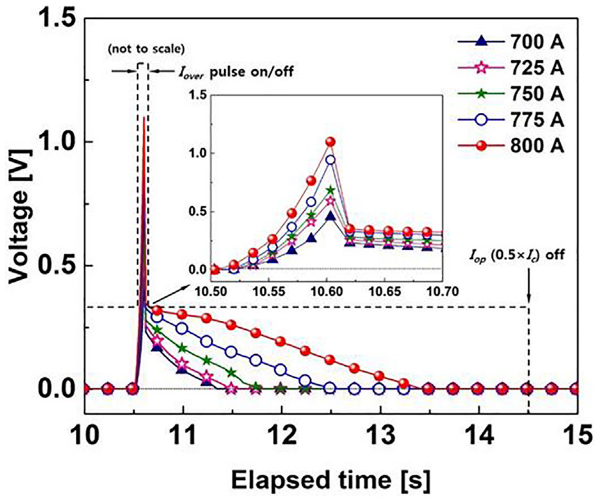
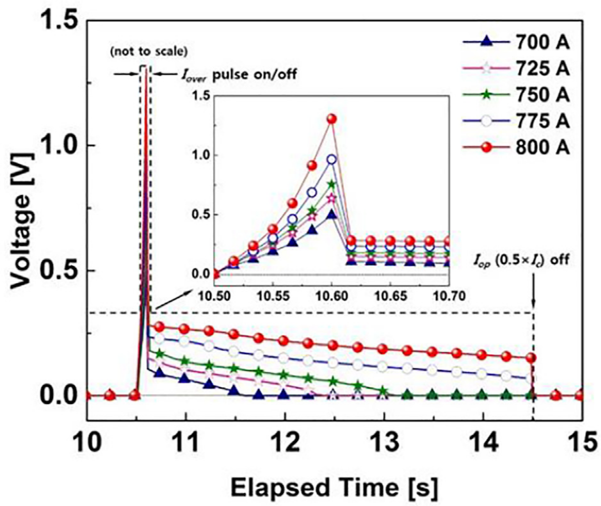
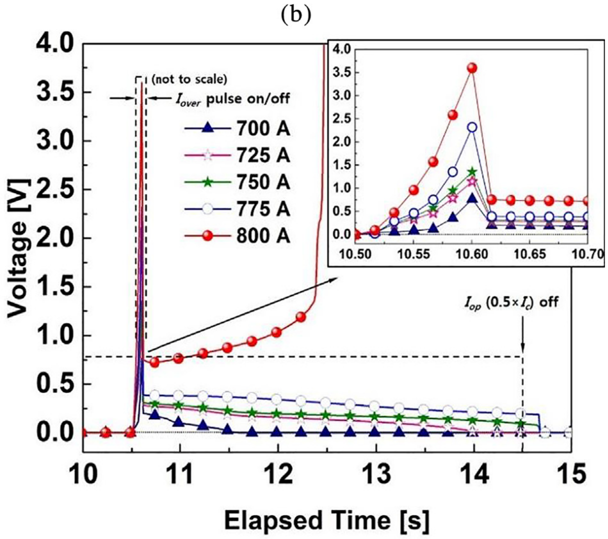


(a)



(b)



(c)

Fig. 6. Over-current test results of samples #1 (a), #2 (b), and #3 (c) with respect to I_{over}.

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