Giant proximity effect in single-crystalline MgB$_2$ bilayers

Soon-Gil Jung$^{1,2}$, Duong Pham$^{2}$, Tae-Ho Park$^{2}$, Han-Yong Choi$^{2}$, Jin Won Seo$^{3}$, Won Nam Kang$^{2}$ & Tuson Park$^{1,2}$

Although giant proximity effect (GPE) can shed important information on understanding superconducting pairing mechanisms and superconducting electronics, reports on the GPE are few because the fabrication of the junctions with GPE is technologically difficult. Here, we report a GPE in the single-crystalline MgB$_2$ bilayers ($S'/S$), where the $S'$ is the damaged MgB$_2$ layer by cobalt (Co)-ion irradiation and the $S$ is the undamaged MgB$_2$ layer. Superconducting properties of the $S'$ is remarkably degraded by the irradiation, whereas those of the $S$ is uninfluenced by the irradiation. The degraded superconductivity in the $S'$ is fully recovered by increasing the thickness of undamaged MgB$_2$ layer $S$ despite almost ten times larger thickness ~95 nm of $S'$ than the superconducting coherence length $\xi_{ab}(0) = 8.5$ nm of the $S$, indicating a presence of GPE in the $S'/S$ MgB$_2$ bilayers. A diffusion of electrons in the $S'$ into the $S$ can reduce a pair breaking scattering in the $S'$, and the similar electronic structures of $S'$ and $S$ layers and a finite attractive electron-electron interaction in the $S'$ are thought to be origins of unpredicted GPE between the same superconducting materials. Both upper critical field ($\mu_0 H_{c2}$) and in-field critical current density ($J_c$) of $S'/S$ bilayers show a significant enhancement, representing a strong correlation between $S'$ and $S$. These discoveries provide the blue print to the design of the superconducting multilayers for fundamental researches on the mechanism of the GPE as well as their technological applications.

The superconducting proximity effect (PE), a leak of Cooper pairs from a superconductor ($S$) into a normal metal ($N$) when they are in contact with each other, is a fascinating phenomenon that is critical to the design of superconducting electronic devices, such as superconducting quantum interface device (SQUID) and quantum information device$^{1-4}$. Superconducting coherence length ($\xi$) and electronic mean free path ($l$) in the normal metal are important parameters to determine the leaking distance of Cooper pairs in $S/N$ junctions, which have been intensively studied and well understood based on conventional theories$^{5-10}$.

Recently, unpredicted large PE was observed when superconductor $S_1$ is connected with another superconductor $S_2$ instead of normal metal, which is known as the giant proximity effect (GPE)$^{11-17}$. Here, superconducting transition temperature ($T_c$) of $S_2$ is lower than that of $S_1$. The Cooper-pair leaking distance in $S_1/S_2$ junctions is almost ten times larger than the coherence length $\xi$, and Josephson critical current could be much improved in the superconducting multilayers composed of the optimally doped and under doped high-$T_c$ cuprates, such as LSCO (La$_{2-}\delta$Sr$_\delta$CuO$_4$)/LCO (La$_2$CuO$_4$)/LSCO trilayer$^{13-15}$. The spatially long-ranged propagation of Cooper pairs between two different conventional superconductors, such as few-layer lead (Pb) island and Pb monolayer, was also visualized by using scanning tunnelling spectroscopy (STS) and scanning tunnelling microscopy (STM)$^{16,17}$. The Cooper pairs’ leaking distance is influenced by the $T_c$ of $S_2$, which is considered due to its finite attractive interactions/phase fluctuations or an additional superconductivity between the interface of $S_1$ and $S_2$. However, the origin of GPE has yet to be clarified$^{12-15,18}$.

GPE is expected to provide a significant technological advantage for the applications of superconducting electronics because thicker barrier can make it much easier to achieve uniform Josephson junctions. GPE observed in the cuprates-based Josephson junctions, however, has shown inconsistent results partly because of the surface roughness between layers and secondary phases$^{13,15}$. Fabrication of the uniform multilayers in such complex compounds has proven to be difficult so far.

Ion irradiations have been often used to fabricate $S/N/S$ Josephson junctions because local crystal disorders or defects can easily be controlled by an irradiating ion source or its dose$^{19-23}$, and long range PE has been also

$^{1}$Center for Quantum Materials and Superconductivity (CQMS), Sungkyunkwan University, Suwon, 16419, Republic of Korea. $^{2}$Department of Physics, Sungkyunkwan University, Suwon, 16419, Republic of Korea. $^{3}$Department of Materials Engineering, KU Leuven, Kasteelpark Arenberg 44-bus 2450, B-3001, Leuven, Belgium. Correspondence and requests for materials should be addressed to W.N.K. (email: wnkang@skku.edu) or T.P. (email: tp8701@skku.edu)
observed in the junctions fabricated by ion irradiations. Similar electronic structures between S and N layers and a finite SC pairing interaction in the N layer are considered as sources for the enhanced proximity effect. Conventional superconductor MgB$_2$ with relatively high $T_c$ of 40 K is a good candidate for GPE realization via the ion irradiation technique because of its large superconducting coherence length, metallicity, and large superconducting energy gap.

Here we report the giant proximity effect in the S′/S MgB$_2$ bilayers. A dose of 1 × 10^{14} Co atoms/cm$^2$ with the 140 keV beam energy (mean projected range $\delta = 95$ nm), where $\delta$ is the average distance from the surface of the film at which the irradiated Co ions come to maximum concentration, is irradiated into single-crystalline MgB$_2$ films with various thicknesses ($t$) of 130, 200, 410, 850, and 1300 nm. $T_c$ of the MgB$_2$ film with $t = 130$ nm is considerably suppressed from 38.2 to 4.5 K after the Co-irradiation. Although, the thickness of damaged MgB$_2$ layer (S′) by the irradiation is almost ten times longer than the coherence length, $\xi_0(0) ∼ 8.5$ nm, of the undamaged MgB$_2$ layer (S), the suppressed $T_c$ of S′ by the irradiation is rapidly restored to that of the pristine state with an increase in the thickness of S. In addition, upper critical field ($\mu_0H_c(2)$) of the S′/S bilayers has two times larger value than that of the pristine films, and field performance of critical current density ($J_c$) of the bilayers is superior to that of the pristine MgB$_2$ films. These results demonstrate that the existence of giant proximity effect in the S′/S MgB$_2$ bilayers provides a blue print to fabricate superconducting MgB$_2$ multilayers for their fundamental researches as well as technological applications.

**Results**

Figure 1(a) shows the mean projected range ($\delta = 95$ nm) of the irradiated 140 keV Co ions into MgB$_2$ and damage events created by the irradiated energetic ions, simulated by the SRIM program. If MgB$_2$ film is thick enough compared to the $\delta$, it can be divided into two layers: damaged layer (S′) and undamaged layer (S). Superconducting (SC) properties of the S is expected to be the same with that of the pristine state, while the SC properties of the S′ will be changed by the ion-irradiation conditions. In order to investigate the correlation between S′ and S, we considered two types of electrode configurations, i.e., 4-point contact method A and B, as described in the insets of Fig. 1(a). In contact method A, the 4 probes are directly connected to the S, whereas they are in contact with the S′ in contact method B.

The solid lines in Fig. 1(b) indicate the temperature dependences of electrical resistivity ($\rho$) for the pristine MB850 nm at magnetic fields of 2 and 4 T, where $\rho(T)$ is normalized by the $\rho$ value at $T_0$ onset, $\rho_0$, at each magnetic field for comparison. After irradiation with a dose of 1 × 10^{14} Co atoms/cm$^2$ in the MB850 nm, $\rho(T)$ was measured again by using the 4-point contact method A and B. For the contact method B, the resistivity drop of the irradiated film at $T_c$ is sharper and more robust than that of the pristine: at 4 Tesla, the zero-resistance state is suppressed to 19.1 K for the irradiated film, while it is 4.8 K for the pristine. The $\rho(T)$ curves measured by the contact method A, in contrast, show two SC transitions: the first SC transition is consistent with the SC transition of the S′ measured by the contact method B and the second SC transition is similar to the SC transition of the pristine sample. These results delineate that S′/S MgB$_2$ bilayer is fabricated via the ion irradiation method.

The $\rho(T)$ curve near $T_c$ for pristine MgB$_2$ films of MB130 nm, MB200 nm, MB410 nm, MB850 nm, and MB1300 nm is shown in Fig. 2(a), where $\rho(T)$ is normalized by the $\rho$ value at 41 K, $\rho(41K)$. With decreasing film thickness, $T_c$ of the pristine MgB$_2$ films slightly decreases and the SC transition remains sharp, except the thinnest MB130 nm (ref.28) (see Fig. S1 in the Supplemental Information). On the other hand, $T_c$ of the S′/S MgB$_2$ bilayers is rapidly suppressed with decreasing the thickness ($t'$) of undamaged MgB$_2$ layer S, as shown in Fig. 2(b), where $\rho(T)$ was measured by using the contact method A. The change in $T_c$ of the S′/S bilayers is linked to $t'$ because the same dose of Co ions with the same incident energy of 140 keV was irradiated. The large suppression of $T_c$ from 38.2 to 4.5 K in MB130 nm after the irradiation indicates that a dose of 1 × 10^{14} Co atoms/cm$^2$ is enough to substantially degrade superconductivity of the MgB$_2$. Interestingly, however, $T_c$ is rapidly restored back to the original value with increasing film thickness. Temperature dependences of dc magnetization (M) also showed similar results to the $\rho(T)$ curve (Fig. S2 in the Supplemental Information), indicating that the SC transition in the S′/S bilayers is not originated from filamentary nature. In addition, the fact that the thickness of damaged MgB$_2$ layer (S′) is much larger than the coherence length (\xi) of MgB$_2$ (ref.29) indicates the emergence of giant proximity effect (GPE) in S′/S MgB$_2$ bilayers. We note that the GPE is often observed in junctions fabricated by ion irradiations. Similar electronic structures between S′ and S, where S′ and S are superconducting layers with different $T_c$ (refs.11-17).

Figure 2(c) displays the SC transition temperature of the irradiated MgB$_2$ films ($T_{c,irr}$), normalized by that of the pristine films ($T_{c,pri}$), as a function of the reduced film thickness $t'/\delta$, where $t' = (t - \delta)$ represents the thickness of the undamaged layer (S) and $\delta$ corresponds to the thickness of the damaged layer (S′). Here, $T_{c,pri}$ and $T_{c,irr}$ are determined from the criterion of 50% resistivity drop from the resistivity value at 41 K. For comparison, $T_{c,irr}/T_{c,pri}$ for S′/S bilayers with $\delta = 27$ (stars) and 49 nm (circles) are also plotted in Fig. 2(c), where a beam energy of 35 (27.3 nm) and 70 keV (49.4 nm) was used with the same dose of 1 × 10^{14} Co atoms/cm$^2$. Inset of Fig. 2(c) shows $T_{c,pri}$ and $T_{c,irr}$ as a function of the $t'/\delta$ for pristine and irradiated MgB$_2$ films, respectively. $T_{c,irr}$ that corresponds to the $T_c$ of S′/S bilayers is monotonically reduced with decreasing $t'/\delta$ and is completely suppressed to 0 K at the critical ratio $t'/\delta ∼ 0.19$, i.e. 19% of the thickness of S that to that of S′. For $\delta = 95$ nm, for instance, the critical thickness ($T_{c,irr} = 0$ K) of the S′/S MgB$_2$ bilayer is 113 nm.

**Discussion**

The thickness ratio ($t'/\delta$) dependence of the SC transition temperature for the S′/S bilayers is expressed by the Wetherhame theory considered the spatial variation of electron-electron interaction, even though the thicknesses of the S and S′ are much thicker than coherence length of MgB$_2$. In the BCS theory, $T_c$ of a normal metal (N) and superconductor (S) bilayer can simply be expressed by the relation

$$T_c = 1.14\Theta_D\exp\left[-\frac{1}{(N_0V_0)_{eff}}\right],$$

where $\Theta_D$ is Debye temperature, $N_0$ is the electronic density of states at the Fermi energy, and $V_0$ is strength of attractive electron-electron interaction, and $(N_0V_0)_{eff}$ is the effective BCS interaction parameter. For N/S bilayer, $N_0V_0$
in the S layer is an important parameter to determine \( T_c \) of the bilayer, because \( V_0 = 0 \) in the N layer. On the other hand, a finite \( V_0 \) in the N layer could induce the long range of the PE due to the slow decay of SC pair amplitude in the N layer\(^{16,18,24}\), which is probably one of the primary reasons for GPE in the \( S'/S \) MgB\(_2\) bilayer.

The electronic density of states at the Fermi energy (\( N_0 \)) is also important to determine \( T_c \), and the large reduction of \( T_c \) in MgB\(_2\) by the irradiation is believed to be due to the decreased \( N_0 \) and enhanced interband scattering\(^{30-34}\). Considering a significant decrease of \( T_c \) of MB130 nm from 38.2 to 4.5 K by Co-ion irradiation, the \( T_c \) variation in the \( S'/S\) MgB\(_2\) bilayers is expressed by the decrease in the \( N_0 \) (refs\(^{29,35,36}\)). Figure 2(d) shows that the inverse of \( T_c \) difference between the pristine and irradiated films, \( 1/\Delta T_c (= T_{c,\text{prin}} - T_{c,\text{irr}}) \), is linearly proportional to the thickness ratio between the undamaged (\( t' \)) and damaged MgB\(_2\) layers (\( t \)), \( t'/t \), indicating that the \( T_c \) suppression by the Co-ion irradiation is closely related with the decrease in the electronic density of states \( N_0 \) of the damaged layer \( S' \) (refs\(^{29,35,36}\)). The initial slope of \( T_c \) (\( \propto |dT_c/dN_0| \)) in S/N bilayer is proportional to the ratio of density of states between the two layers (\( N_0/N_1 \)) because \( T_c = 1.14 \Theta_D \exp[-1/(N_0 V_0)] \), where \( N_0 \) and \( N_1 \) are the
ρ(T) curves near the SC transitions for (a) pristine and (b) Co-ion irradiated MB130 nm, MB200 nm, MB410 nm, MB850 nm, and MB1300 nm, where ρ(T) was normalized by the ρ at 41 K, ρ(41 K), for comparison. (c) The SC transition temperature of the irradiated films (Tc, irr.) as a function of t′/δ, where the Tc, irr. is normalized by Tc of the pristine films (Tc, pri.) and t′ (= l − δ) is the thickness of the S. Star, circle, and square symbols represent Tc for different incident energies of 35 (δ ~ 27 nm), 70 (δ ~ 49 nm), and 140 keV (δ ~ 95 nm), respectively. Both Tc, pri. and Tc, irr. are determined from the midpoint of SC transition, ρ(41 K), 50% resistivity drop from the ρ(0). The red solid line is a fitting curve by using the Werthamer theory. Inset shows the Tc, pri. and Tc, irr. as a function of t′/δ. (d) The inverse of the Tc reduction, 1/ΔTc (=Tc, pri. − Tc, irr.), is plotted as a function of t′/δ.

**Figure 2.** Thickness dependence of superconducting transition temperature for irradiated MgB2 films. ρ(T) curves near the SC transitions for (a) pristine and (b) Co-ion irradiated MB130 nm, MB200 nm, MB410 nm, MB850 nm, and MB1300 nm, where ρ(T) was normalized by the ρ at 41 K, ρ(41 K), for comparison. (c) The SC transition temperature of the irradiated films (Tc, irr.) as a function of t′/δ, where the Tc, irr. is normalized by Tc of the pristine films (Tc, pri.) and t′ (= l − δ) is the thickness of the S. Star, circle, and square symbols represent Tc for different incident energies of 35 (δ ~ 27 nm), 70 (δ ~ 49 nm), and 140 keV (δ ~ 95 nm), respectively. Both Tc, pri. and Tc, irr. are determined from the midpoint of SC transition, ρ(41 K), 50% resistivity drop from the ρ(0). The red solid line is a fitting curve by using the Werthamer theory. Inset shows the Tc, pri. and Tc, irr. as a function of t′/δ. (d) The inverse of the Tc reduction, 1/ΔTc (=Tc, pri. − Tc, irr.), is plotted as a function of t′/δ.

We consider the diffusion of electrons inside the damaged S′ into the undamaged S as well as the diffusion of Cooper pairs from the S to S′. Those diffusion processes by the electrons and the Cooper pairs can lead the extension of the proximity region in terms of the strong correlation between S and S′. In particular, when the thickness of S is large, there can be enough space for the diffusion of electrons from the S′ into S. This interpretation is supported by the study on the lower and upper critical fields and critical current density for S′/S MgB2 bilayers, which will be discussed below.

Figure 3(a,b) show the ρ(T) curves in magnetic fields for the pristine and Co-ion irradiated MB410 nm, respectively, where the ρ(T) is normalized by the resistivity value in the normal state (ρ0) for each magnetic field. In stark contrast to the pristine film, two-step SC transitions appear in the ρ(T,H) measured by the 4-probe contact method A for the Co-ion irradiated MB410 nm. The second SC transition temperature (Tc′) is consistent with the SC transition temperature of pristine films (Tc, pri.), indicating that Tc′ emerged at high magnetic fields is originated from superconductivity in the S. When the contact method B was used, on the other hand, there is no trace of Tc′ in ρ(T,H) curves because the 4 probes of the contact method B are not directly in contact with the damaged layer and the supercurrent flows mainly through the damaged layer S′.

Temperature dependences of the upper critical field (μ0Hc2) for the pristine and irradiated MB410 nm and MB850 nm are presented in Fig. 3(c,d), respectively, where the magnetic field is applied perpendicular to the film’s ab plane (H ⊥ ab) plane. The criteria for Tc, pri. and Tc, irr. are 50% resistivity drop for the pristine and irradiated films, respectively, while Tc, pri. and Tc, irr. are assigned as the 50% resistivity drop of the second SC transition and a kink temperature of the first SC transition, respectively (see the arrows in Fig. 3(a,b)). The magnetic field dependence of the kink temperature (Tc, k) for the MB410 nm suggests that Tc, k is associated with Tc of the undamaged layer S. One the other hand, there is no kink (Tc, k) in the irradiated MB850 nm because superconductivity of the damaged layer S′ is completely restored to that of the pristine state, i.e., Tc, pri. ≈ Tc, irr. The fact that μ0Hc2(Tc, k) is consistent with those estimated from the Tc, pri. underscores that the MgB2/MgB2 bilayer is formed by the Co-ion irradiation. Upper critical field of the bilayers is enhanced by two times to the pristine films: μ0Hc2(0) = 5.29 → 9.75 T for MB410 nm and μ0Hc2(0) = 4.52 → 9.50 T for MB850 nm, which can be accounted for by additional
defects introduced via the Co-ion irradiation. The SC coherence length, $\xi_{ab}(0)$, obtained from the $\mu_0 H_c^2(0)$ is reduced from 7.89 to 5.81 nm and from 8.54 to 5.89 nm for MB410 nm and MB850 nm after the irradiation, respectively.

Temperature dependence of $\mu_0 H_c^2$ is reasonably explained by the two-band Ginzburg-Landau theory, indicated by the red dashed lines in Fig. 3(c,d). According to Takahashi-Tachiki model in $S_1/S_2$ superlattices, an upturn behavior in $H_c^2(T)$ can be observed near $T_c$ due to different spatial variations in the density of states, the diffusion constant, and the electron-electron attractive interaction potential between $S_1$ and $S_2$ (refs38,39). The enhanced upturn feature of $\mu_0 H_c^2(T)$ in the MgB2 bilayer (MB850 nm) compared to that in the pristine film may be closely associated with the different diffusion constant between $S$ and $S'$ layers because $T_{c,pri.} \approx T_{c,irr.}$ in the MB850 nm. The Cooper pairs in the damaged layer may be more effective in penetrating into the undamaged layer, inverse proximity effect16,23, than the reversal process because of a larger diffusion constant in the $S$ than $S'$ layer, leading to the large upturn feature in $\mu_0 H_c^2(T)$ near $T_c$. On the other hand, Ferrando et al. suggested that a large upward behavior of $H_c^2(T)$ in high magnetic field parallel to the $ab$ plane ($H//ab$) will be needed because this upturn behavior or sudden change of $\mu_0 H_c^2(T)$ in $S'/S$ is more prominent for $H//ab$ (refs38,39).

Magnetic field dependences of critical current density ($J_c$) for the pristine and irradiated MgB2 films at 5 and 20 K are shown in Fig. 4(a,b), respectively, where the magnetic field is applied perpendicular to the film's $ab$ plane. The large $J_c$ at zero field and its rapid suppression in magnetic fields indicate that the pristine MgB2 films used in this study is clean42,43. After Co-ion irradiation, in-field $J_c$ is significantly improved except for the thinnest MB130 nm film because of the large suppression of $T_c$. The suppression of zero-field $J_c$ for the irradiated MB410 nm is also related with the suppressed $T_c$ by the irradiation. On the other hand, in-field $J_c$ for both MB850 nm and MB1300 nm is remarkably enhanced without the suppression of the zero-field $J_c$ after Co-ion irradiation, suggesting that the proximity effect (PE) in the $S'/S$ bilayers is not confined near the interface11–13, but is long ranged over the whole thickness of the irradiated layer $S'$ when the thickness of the $S$ is sufficiently larger than that of the $S'$. In addition, the large in-field $J_c$ in $S'/S$ MgB2 bilayers manifests the strong correlation between $S'$ and $S$ layers.
Conclusion

In conclusion, we reported fabrication of MgB$_2$/MgB$_2$ bilayers, where a dose of $1 \times 10^{14}$ Co atoms/cm$^2$ with a beam energy of 140 keV is irradiated into single-crystalline MgB$_2$ films and created the damaged layer ($S'$) inter-faced with the undamaged layer ($S$). Superconductivity of MgB$_2$ in the damaged layer is significantly weakened: $T_c$ is suppressed from 38.2 to 4.5 K for the irradiated MB130 nm film. The suppressed superconductivity, however, was restored to the original SC state when the thickness of the undamaged MgB$_2$ layer ($S$) is sufficiently larger than that of the damaged MgB$_2$ layer ($S'$). Although the coherence length of the undamaged layer $S$ ($\sim 8.5$ nm) is more than ten times shorter than the damaged layer $S'$ ($\sim 95$ nm), the proximity effect occurs over the whole thickness of the $S'$. This anomalously long-ranged proximity effect in $S'/S$ MgB$_2$ bilayers is thought to be originated from the similar electronic structures of $S'$ and $S$ layers and a finite SC pairing interaction in the $S'$ layer. The discovery of giant proximity effect (GPE) in the MgB$_2$/MgB$_2$ bilayers is expected to provide a blueprint to the design of superconducting MgB$_2$ multilayers for their fundamental researches as well as technological applications.

Figure 4. Critical current density $J_c$ of MgB$_2$/MgB$_2$ bilayer. Magnetic field dependences of the critical current density ($J_c$) at (a) 5 and (b) 20 K for the pristine and Co-ion irradiated MB130 nm, MB410 nm, MB850 nm, and MB1300 nm. $J_c$ for all pristine films shows a similar field performance, and a rapid decrease of $J_c$ in magnetic fields indicates that the MgB$_2$ films used in this study is of high quality. A significant enhancement of in-field $J_c$ after irradiation is observed except for the MB130 nm. There is no data for the $J_c$ of the irradiated MB130 nm due to a substantially suppressed $T_c$ and SC volume fraction.
Methods

Hybrid physical-chemical vapour deposition (HPCVD) method was used for the growth of single-crystalline MgB$_2$ films on the c-cut Al$_2$O$_3$ substrates, and the details of the growth technique and the films single-crystal quality are described elsewhere$^{34,44}$. The MgB$_2$ films with various thicknesses ($t$) of 130 (MB130 nm), 200 (MB200 nm), 410 (MB410 nm), 850 (MB850 nm), and 1,300 nm (MB1300 nm) were fabricated for ion irradiations, and the same dose of $1 \times 10^{14}$ Co atoms/cm$^2$ with 140 keV beam energy at room temperature was irradiated into the prepared MgB$_2$ films in Korea Multi-purpose Accelerator Complex (KOMAC). The mean projected range ($\delta$) of irradiated Co ions is around 95 nm, which is simulated by the Monte Carlo simulation program SRIM (The Stopping and Range of Ions in Matter)$^{27}$.

The formation of S/S MgB$_2$ bilayers by the Co-ion irradiation was confirmed by simultaneously measuring electrical resistivity ($\rho$) of the damaged and undamaged MgB$_2$ layers in Physical Property Measurement System (PPMS 9T, Quantum Design). The standard 4-probe method was used for electrical resistivity measurements, and the 4-point contact regions were protected from the irradiation by using gold (Au) coating and silver (Ag) epoxy in order to measure the resistivity of the undamaged layer after the irradiation. In order to estimate the critical current density ($J_c$), magnetization hysteresis ($M-H$) loops were measured by using a Magnetic Property Measurement System (MPMS 5T, Quantum Design) before and after the Co-ion irradiations (see Fig. S3 in the Supplemental Information).

References

1. Meissner, H. Superconductivity of contacts with interposed barriers. Phys. Rev. 117, 672 (1960).
2. de Gennes, P. G. Boundary effects in superconductors. Rev. Mod. Phys. 36, 225 (1964).
3. Likharev, K. K. Superconducting weak links. Rev. Mod. Phys. 51, 101 (1979).
4. Makhlin, Y., Schön, G. & Shnirman, A. Quantum-state engineering with Josephson-junction devices. Rev. Mod. Phys. 73, 357 (2001).
5. Hilsch, P. & Hilsch, R. Zur Supraleitung von Schichtpaketen aus Normal- und Supraleitern. Z. Phys. 180, 10 (1964).
6. Werthamer, N. R. Theory of the superconducting transition temperature and energy gap function of superposed metal films. Phys. Rev. 132, 2440 (1963).
7. Kircher, C. J. Superconducting proximity effect of Nb. Phys. Rev. 168, 437 (1968).
8. Hauser, J. J., Theuerer, H. C. & Werthamer, N. R. Superconductivity in Cu and Pt by means of superimposed films with lead. Phys. Rev. 136, A637 (1964).
9. de Gennes, P. G. & Guyon, E. Superconductivity in “normal” metals. Phys. Lett. 3, 168 (1963).
10. Kim, J., Doh, Y.-J., Cha, K., Doh, H. & Choi, H.-Y. Proximity effect in Nb/Au/CoFe trilayers. Phys. Rev. B 71, 214519 (2005).
11. Decca, R. S., Drew, H. D., Osquiugili, E., Maiorov, B. & Guimpel, J. Anomalous proximity effect in underdoped YBa$_2$Cu$_3$O$_{6+\delta}$ Josephson junctions. Phys. Rev. Lett. 85, 3708 (2000).
12. Marchand, D., Covaci, L., Berciu, M. & Franz, M. Giant proximity effect in a phase-fluctuating superconductor. Phys. Rev. Lett. 101, 097004 (2008).
13. Bozovic, I. et al. Giant proximity effect in cuprate superconductors. Phys. Rev. Lett. 93, 157002 (2004).
14. Covaci, L. & Marsiglio, F. Proximity effect and Josephson current in clean strong/weak superconducting trilayers. Phys. Rev. B 73, 014503 (2006).
15. Rout, P. K. & Budhani, R. C. Interface superconductivity in La$_1.48$Nd$_0.4$Sr$_{0.12}$CuO$_4$/La$_{1.84}$Sr$_{0.16}$CuO$_4$ bilayers. Phys. Rev. B 82, 024518 (2010).
16. Cherkez, V. et al. Proximity effect between two superconductors spatially resolved by scanning tunneling microscopy. Phys. Rev. X 4, 011033 (2014).
17. Kim, J. et al. Visualization of geometric influences on proximity effects in heterogeneous superconductor thin films. Nat. Phys. 8, 464 (2012).
18. Quintanilla, J., Capelle, K. & Oliveira, L. N. Comment on “Anomalous proximity effect in underdoped YBa$_2$Cu$_3$O$_{6+\delta}$ Josephson junctions”. Phys. Rev. Lett. 90, 089703 (2003).
19. Kahlmann, F. et al. Superconductor–normal–superconductor Josephson junctions fabricated by oxygen implantation into YBa$_2$Cu$_3$O$_{6+\delta}$. J. Appl. Phys. Lett. 73, 2354 (1998).
20. Cybart, S. A. et al. Planar MgB$_2$ Josephson junctions and series arrays via nanolithography and ion damage. Appl. Phys. Lett. 88, 012509 (2006).
21. Kang, D.-J. et al. Realization and properties of YBa$_2$Cu$_3$O$_{6+\delta}$ Josephson junctions by metal masked ion damage technique. Appl. Phys. Lett. 80, 814 (2002).
22. Sirena, M. et al. Annealing of ion irradiated high $T_c$ Josephson junctions studied by numerical simulations. J. Appl. Phys. 105, 023910 (2009).
23. Sharafiev, A. et al. HTS Josephson junctions arrays for high-frequency mixing. Supercond. Sci. Technol. 31, 035003 (2018).
24. Tachiki, M. & Takahashi, S. Proximity effect in high-$T_c$ oxide superconductors. Phys. C 191, 363 (1992).
25. Cybart, S. A. et al. Large scale two-dimensional arrays of magnesium diboride superconducting quantum interference devices. Appl. Phys. Lett. 104, 182604 (2014).
26. Gdaim, E., Cunnane, D., Xi, X. & Chen, K. Sandwich-type MgB$_2$/TiB$_2$/MgB$_2$ Josephson junctions. Supercond. Sci. Technol. 27, 065015 (2014).
27. The projected range of Co ions in the MgB$_2$ film was calculated using the SRIM software. (www.srim.org/).
28. Pogrebnjakov, A. V. et al. Thickness dependence of the properties of epitaxial thin films grown by hybrid physical-chemical vapor deposition. Appl. Phys. Lett. 82, 4319 (2003).
29. Zhang, M., Tateishi, G. & Bergmann, G. Discrepancies between experiment and theory in the superconducting proximity effect. Phys. Rev. B 74, 014506 (2006).
30. Ferrando, V. et al. Neutron irradiation effects on two gaps in MgB$_2$, Physica C 456, 144 (2007).
31. Gerashenko, A. P., Mikhailev, K. N., Verkhovski, S. V., Karkin, A. E. & Goshchitskii, B. N. Reduction in the electron density of states in superconducting MgB$_2$, disordered by neutron irradiation: $^{18}$O and $^{27}$Mg NMR estimates. Phys. Rev. B 65, 132506 (2002).
32. Vinod, K., Varghese, N. & Syamprasad, U. Superconductivity of MgB$_2$ in the BCS framework with emphasis on extrinsic effects on critical temperature. Supercond. Sci. Technol. 20, R31 (2007).
33. Petti, M., Vaglio, R. & Rowell, J. M. Radiation effects on MgB$_2$: a review and a comparison with A15 superconductors. Supercond. Sci. Technol. 21, 043001 (2008).
34. Petti, M. et al. Intraband vs. interband scattering rate effects in neutron irradiated MgB$_2$. EPL 77, 57005 (2007).
35. Bergmann, G. Quantitative simulation of the superconducting proximity effect. Phys. Rev. B 72, 134505 (2005).
36. Garrett, D., Zhang, M. & Bergmann, G. The superconducting proximity effect as a tool to investigate metal films and interfaces. Eur. Phys. J. B 39, 199 (2004).
37. Tinkham, M. Introduction to Superconductivity, 2nd ed (McGraw- Hill, New York, 1996).
38. Takahashi, S. & Tachiki, M. Theory of the upper critical field of superconducting superlattices. Phys. Rev. B 33, 4620 (1986).
39. Takahashi, S. & Tachiki, M. New phase diagram in superconducting superlattices. Phys. Rev. B 34, 3162 (1986).
40. Ferrando, V. et al. Systematic study of disorder induced by neutron irradiation in MgB$_2$ thin films. J. Appl. Phys. 101, 043903 (2007).
41. Gurevich, A. Enhancement of the upper critical field by nonmagnetic impurities in dirty two-gap superconductors. Phys. Rev. B 67, 184515 (2003).
42. Hanna, M. et al. Clean epitaxial MgB$_2$ films fabricated by the ex situ annealing of chemical vapour deposition-grown B films in Mg vapour. Supercond. Sci. Technol. 21, 045005 (2008).
43. Jung, S.-G., Seong, W. K. & Kang, W. N. Flux pinning mechanism in single-crystalline MgB$_2$ thin films. J. Phys. Soc. Jpn. 82, 114712 (2013).
44. Seong, W. K., Oh, S. & Kang, W. N. Perfect domain-lattice matching between MgB$_2$ and Al$_2$O$_3$: Single-crystal MgB$_2$ thin films grown on sapphire. Jpn. J. Appl. Phys. 51, 083101 (2012).

Acknowledgements
We wish to acknowledge the outstanding support of the accelerator group and operators of KOMAC (Korea Multi-purpose Accelerator Complex), KAERI. This work was supported by the National Research Foundation (NRF) of Korea by a grant funded by the Korean Ministry of Science, ICT and Planning (No. 2012R1A3A2048816) and the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2016R1D1A1B03934513, NRF-2015R1D1A1A01060382, and 2018R1D1A1B07048987).

Author Contributions
S.-G.J. conceived the work and performed the transport and magnetization measurements. D.P. and W.N.K. fabricated single-crystalline MgB$_2$ thin films. S.-G.J., T.-H.P., H.-Y.C. and J.W.S. analysed the data and discussed the results with all authors. The manuscript was written by S.-G.J., W.N.K. and T.P. with inputs from all authors.

Additional Information
Supplementary information accompanies this paper at https://doi.org/10.1038/s41598-019-40263-9.

Competing Interests: The authors declare no competing interests.

Publisher’s note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/.

© The Author(s) 2019