Supporting Information

# Stable and Colorful Perovskite Solar Cells Using a Nonperiodic $SiO_2/TiO_2$ Multi-Nanolayer Filter

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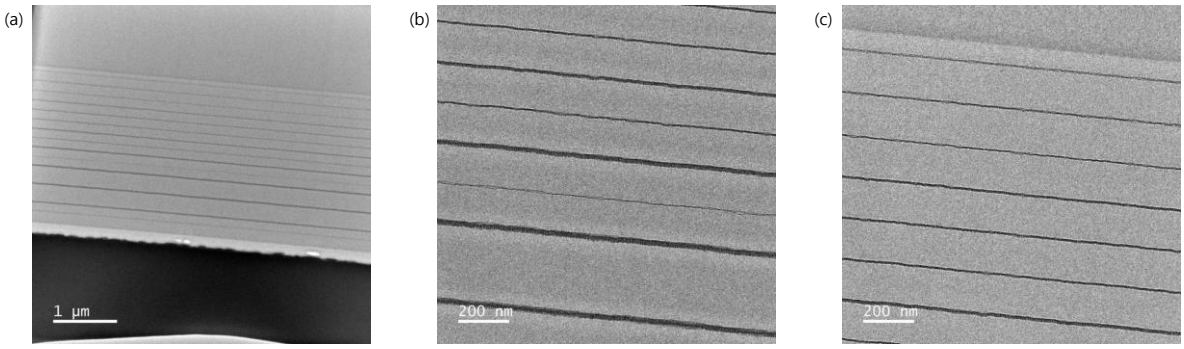


**Figure S1.** FE-TEM images of FIB-sliced (a) nonperiodic blue NBRF at a low resolution, (b) relative nonperiodic stacking region of a blue NBRF at a high resolution, and (c) relative periodic stacking region of a blue NBRF at a high resolution.

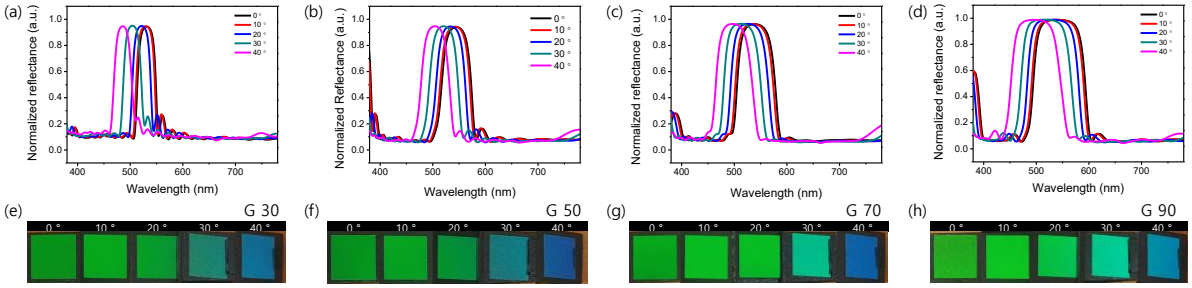


**Figure S2.** Normalized reflectance spectra of G-NBRFs with diverse FWHMs, in this case (a) 30 nm, (b) 50 nm, (c) 70 nm and (d) 90 nm, with various viewing angles ranging from 0° to 40°. Actual images of G-NBRFs with diverse FWHMs, in this case (e) 30 nm, (f) 50 nm, (g) 70 nm and (h) 90 nm from various viewing angles.

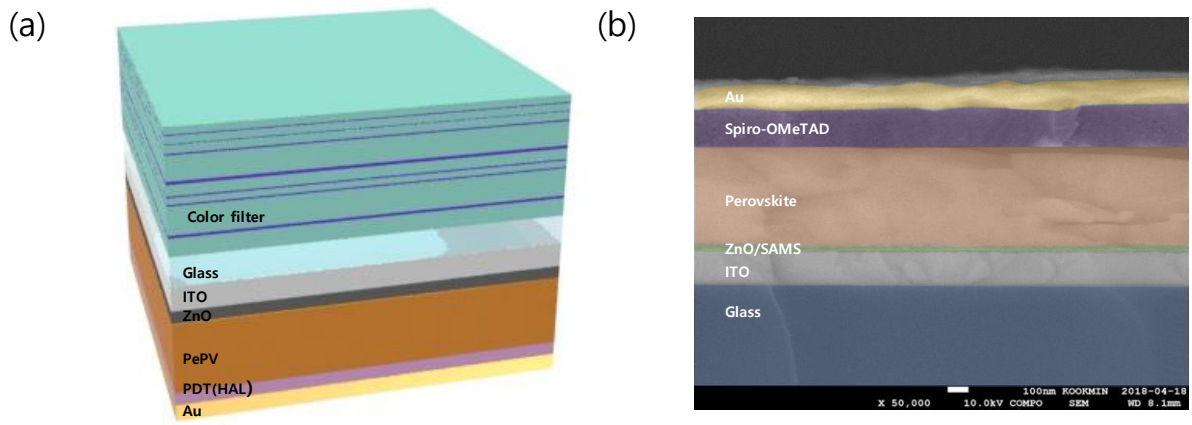


**Figure S3.** (a) Device architecture of PSCs with RGB NBRFs. (b) Cross-sectional FE-SEM image of control PSC.

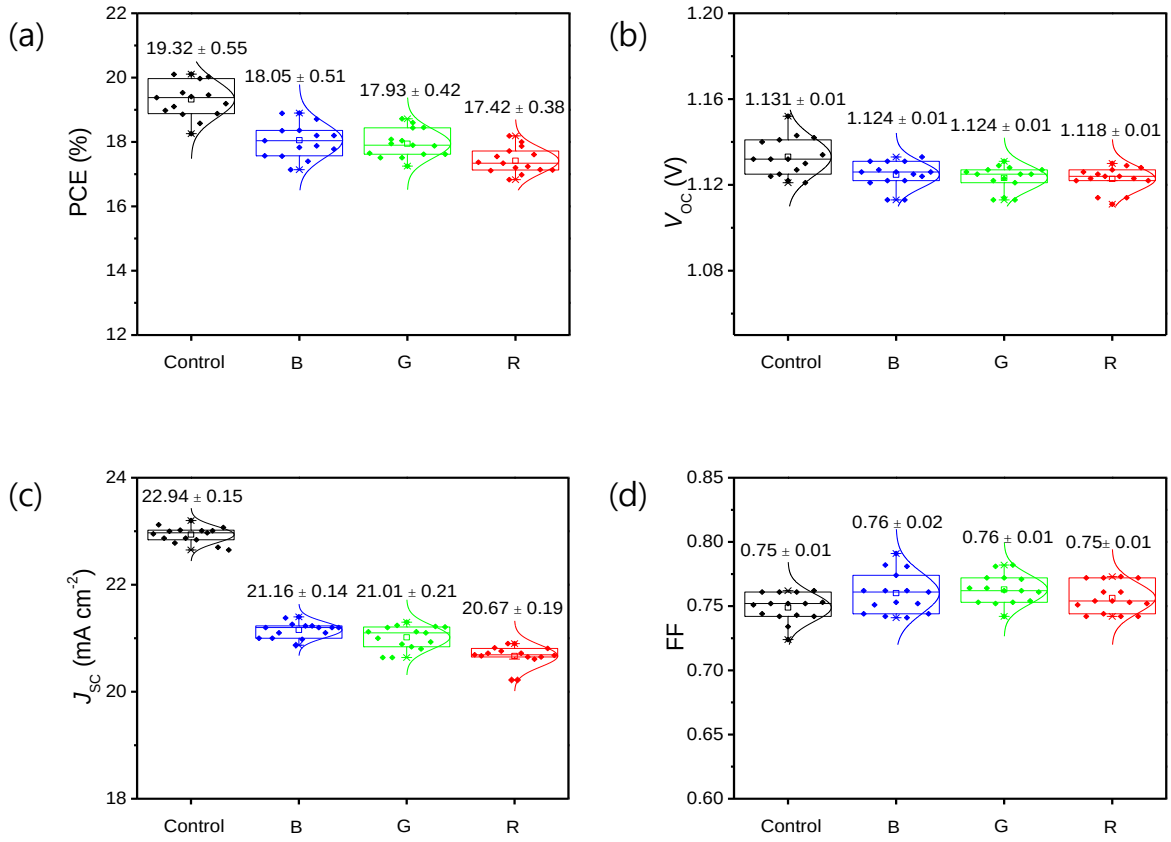


**Figure S4**. Statistical analysis of PSC performance. Statistical data were constructed from 15 devices for each sample.

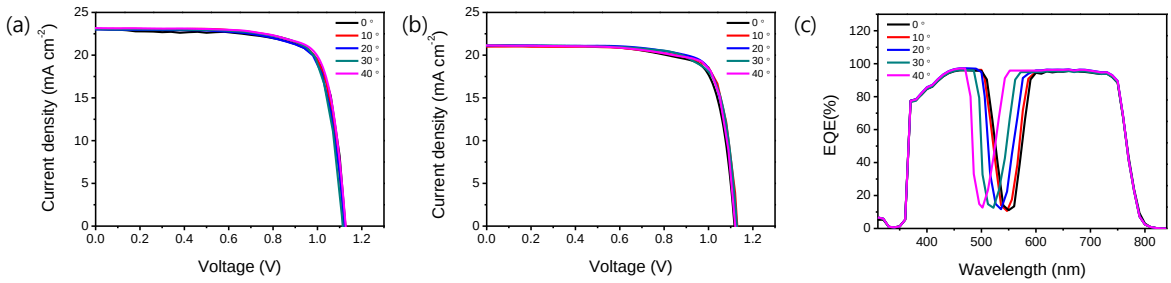


**Figure S5**. *J-V* characteristics of (a) control and (b) G-PSCs at various angles. (c) EQE spectra of G-PSC at various angles.

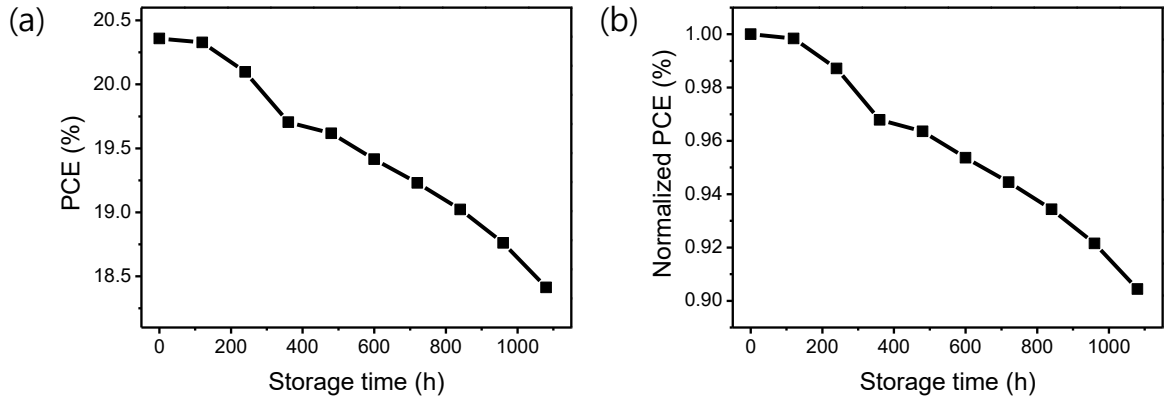


**Figure S6.** Long term degradation of PSCs under $N_2$ atmosphere. The humidity and temperature are 20% and 23 $^{o}$C, respectively.

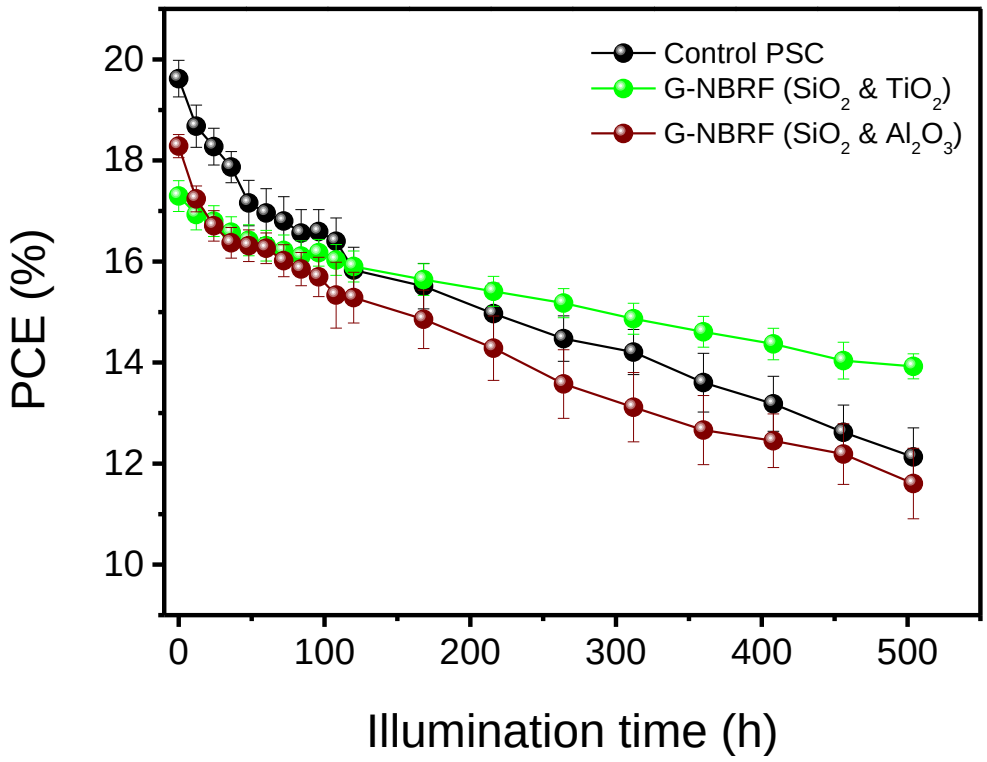


**Figure S7**. Average PCE decay of a control PSC, G-PSC with $SiO_2/Al_2O_3$, and G-PSC with $SiO_2/TiO_2$ for more than 500 h.

**Table S1.** Simulated thicknesses of $SiO_2$ and $TiO_2$ for VBCGYOR NBRFs and G-NBRFs with diverse FWHMs on Glass.

| **$(0.5SiO_2/TiO_2/0.5SiO_2)^n$** | | | | | |
|---|---|---|---|---|---|
| | n = Stacking layer | Wavelength (nm) | $SiO_2$ (nm) | $TiO_2$ (nm) | FWHM |
| Violet | 16 | 422.5 | 129 | 7.75 | 51 |
| Blue | 17 | 463 | 143 | 8 | 50 |
| Cyan | 18 | 495 | 154 | 8.25 | 50 |
| Green | 19 | 536 | 168 | 8.5 | 50 |
| Yellow | 20 | 574 | 181 | 8.75 | 50 |
| Orange | 21 | 606.5 | 192 | 9 | 51 |
| Red | 22 | 636.5 | 202 | 9.25 | 51 |

| **$(0.5SiO_2/TiO_2/0.5SiO_2)^n$** | | | | | |
|---|---|---|---|---|---|
| | n = Stacking layer | Wavelength (nm) | $SiO_2$ (nm) | $TiO_2$ (nm) | FWHM |
| Green (FWHM 30 nm) | 32 | 536.5 | 174.53 | 5 | 30 |
| Green (FWHM 50 nm) | 19 | 536 | 168 | 8.5 | 50 |
| Green (FWHM 70 nm) | 15 | 536.5 | 162 | 12 | 69 |
| Green (FWHM 90 nm) | 11 | 536 | 154.75 | 16 | 90 |

**Table S2.** Simulated thicknesses of nonperiodic RGB NBRFs selected in VBCGYOR NBRFs by a refinement process

| Layer number | Structure | Blue refinement X | Blue refinement O | Green refinement X | Green refinement O | Red refinement X | Red refinement O |
|---|---|---|---|---|---|---|---|
| 1 | $SiO_2$ | 71.5 | 65.88933 | 84 | 77.67077 | 101 | 107.7252 |
| 2 | $TiO_2$ | 8 | 0 | 8.5 | 0 | 9.25 | 9.198262 |
| 3 | $SiO_2$ | 143 | 135.3561 | 168 | 145.7609 | 202 | 178.6347 |
| 4 | $TiO_2$ | 8 | 2.115387 | 8.5 | 2.279439 | 9.25 | 0 |
| 5 | $SiO_2$ | 143 | 143.8693 | 168 | 168.5418 | 202 | 179.5052 |
| 6 | $TiO_2$ | 8 | 13.19121 | 8.5 | 11.63405 | 9.25 | 6.562932 |
| 7 | $SiO_2$ | 143 | 142.9057 | 168 | 185.7984 | 202 | 214.5899 |
| 8 | $TiO_2$ | 8 | 0 | 8.5 | 5.584491 | 9.25 | 10.36592 |
| 9 | $SiO_2$ | 143 | 146.0905 | 168 | 150.5792 | 202 | 211.1014 |
| 10 | $TiO_2$ | 8 | 17.59472 | 8.5 | 9.312838 | 9.25 | 11.03156 |
| 11 | $SiO_2$ | 143 | 143.732 | 168 | 173.5995 | 202 | 206.0357 |
| 12 | $TiO_2$ | 8 | 0 | 8.5 | 8.661671 | 9.25 | 7.532821 |
| 13 | $SiO_2$ | 143 | 141.1505 | 168 | 168.8825 | 202 | 193.0975 |
| 14 | $TiO_2$ | 8 | 18.25221 | 8.5 | 11.10918 | 9.25 | 6.461667 |
| 15 | $SiO_2$ | 143 | 141.9991 | 168 | 158.8519 | 202 | 199.6501 |
| 16 | $TiO_2$ | 8 | 1.732107 | 8.5 | 5.867211 | 9.25 | 10.65542 |
| 17 | $SiO_2$ | 143 | 143.4923 | 168 | 171.0864 | 202 | 204.6748 |
| 18 | $TiO_2$ | 8 | 14.85365 | 8.5 | 14.97218 | 9.25 | 12.22838 |
| 19 | $SiO_2$ | 143 | 143.0101 | 168 | 170.9228 | 202 | 204.2444 |
| 20 | $TiO_2$ | 8 | 4.978768 | 8.5 | 4.894964 | 9.25 | 10.67885 |
| 21 | $SiO_2$ | 143 | 140.9816 | 168 | 159.9573 | 202 | 198.4407 |
| 22 | $TiO_2$ | 8 | 10.77486 | 8.5 | 12.75636 | 9.25 | 8.067185 |
| 23 | $SiO_2$ | 143 | 145.8321 | 168 | 169.81 | 202 | 195.824 |
| 24 | $TiO_2$ | 8 | 6.48939 | 8.5 | 6.823597 | 9.25 | 9.1842 |
| 25 | $SiO_2$ | 143 | 146.5012 | 168 | 167.3449 | 202 | 202.1541 |
| 26 | $TiO_2$ | 8 | 6.671246 | 8.5 | 10.88563 | 9.25 | 11.32312 |
| 27 | $SiO_2$ | 143 | 145.0778 | 168 | 164.5745 | 202 | 204.3591 |
| 28 | $TiO_2$ | 8 | 7.003664 | 8.5 | 4.299725 | 9.25 | 10.59138 |
| 29 | $SiO_2$ | 143 | 148.2741 | 168 | 175.8488 | 202 | 202.5746 |
| 30 | $TiO_2$ | 8 | 3.636205 | 8.5 | 11.44494 | 9.25 | 8.250156 |
| 31 | $SiO_2$ | 143 | 154.3804 | 168 | 172.5244 | 202 | 199.6842 |
| 32 | $TiO_2$ | 8 | 4.625279 | 8.5 | 2.363277 | 9.25 | 7.391081 |
| 33 | $SiO_2$ | 143 | 154.711 | 168 | 168.7576 | 202 | 202.7055 |
| 34 | $TiO_2$ | 8 | 3.514827 | 8.5 | 8.491372 | 9.25 | 8.441495 |
| 35 | $SiO_2$ | 71.5 | 74.42893 | 168 | 176.1996 | 202 | 206.7345 |
| 36 | $TiO_2$ | - | - | 8.5 | 2.82947 | 9.25 | 8.101002 |
| 37 | $SiO_2$ | - | - | 168 | 182.2884 | 202 | 208.8998 |
| 38 | $TiO_2$ | - | - | 8.5 | 5.072185 | 9.25 | 6.346941 |
| 39 | $SiO_2$ | - | - | 84 | 87.4229 | 202 | 208.3755 |
| 40 | $TiO_2$ | - | - | | | 9.25 | 4.919434 |
| 41 | $SiO_2$ | - | - | | | 202 | 207.1847 |
| 42 | $TiO_2$ | - | - | | | 9.25 | 5.652264 |
| 43 | $SiO_2$ | - | - | | | 202 | 216.1687 |
| 44 | $TiO_2$ | - | - | | | 9.25 | 5.35035 |
| 45 | $SiO_2$ | - | - | | | 101 | 111.9933 |

**Table S3**. Summary of device performance of control and G-PSC at various angles.

| Device | Angle | $V_{OC}$ (V) | $J_{SC}$ (mA cm$^{-2}$) | FF (%) | PCE (%) |
|---|---|---|---|---|---|
| Control PSC | 0° | 1.14 | 23.0 | 75 | 19.9 |
| | 10° | 1.14 | 23.1 | 76 | 20.1 |
| | 20° | 1.14 | 23.1 | 76 | 20.1 |
| | 30° | 1.14 | 23.0 | 76 | 20.0 |
| | 40° | 1.14 | 23.2 | 76 | 20.1 |
| G-PSC | 0° | 1.13 | 21.1 | 77 | 18.4 |
| | 10° | 1.13 | 21.0 | 77 | 18.3 |
| | 20° | 1.13 | 21.1 | 77 | 18.4 |
| | 30° | 1.13 | 21.2 | 77 | 18.5 |
| | 40° | 1.13 | 21.2 | 77 | 18.4 |