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In-situ s f - s l s l s l s ff l s f f l s

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A R T I C L E I N F O

Keywords:
T - s l
C s s ff l
S l l s l
C l s
E l f s l

A B S T R A C T

C l , - s l (3DG) f s s l ss, s l s s ll s s l . H l s - s l - s s l l s l (SLM) f - s l (3D) s l . G s *in-situ* l s (CVD) s C l , f 3DG s s. A f l CVD SLM f s ff l l s l s l f 3DG f -s (, s ,) -s (X , s f l) l l l s s ff l . T 3DG/ s ff l l 88% 27% l f (EMI) s l l ff s x s l . P l l , s EMI s l ffi- (*SE*) 47.8 B 2.7 GH x *SE* f 32.3 B f 2–18 GH . T s s s l s s f f s f s l s s f SLM s s .

1. Introduction

G , s s f sp^2 s, s l s f , s s f (2630 ^{2} $^{-1}$) 1 , X ll s l (2 10^5 ^{2} V^{-1} s^{-1}) s l (6 5000 W $^{-1}$ K^{-1}) 2 . H , s π-π s l (2D) s l - s - , s s ff s f s l s s ll, s ll, l , f l - l ss s s s l s f l l 14 . D - ll s s l ll 3 . Af f s l s fi l ff s l s s l - l s. C f s l s, - s l - (3DG) s s s (6 99.7%), l s fi (6 0.6 $^{-2}$) 4 s fi s f s s ll s l , f s l ss sf s f - s l (2DG), X l s l s s 5 , s 6,7 , s s s 4 , l f (EMI) s l 8 s . V s s f s 3DG l , l f 9 , l 10 , s l f- ss l 11 , - ll 12 s . H f - s s ll f s ll s. F x l , f l s ff f l s f s 13 . S l f- ss l s l ss (s l s) l s s s f l s ss l f s s l ss l f s 15 . M s s s l s s sf f f l s , l l - CVD s s s s , s s f l - - l 16 . B s , s l , s s l l f l s s s s

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Available online 18 April 2020

l s . T x s s s (. ., s -
s), \ fl fi l s
(. ., l ss, f s) f 3DG. B s s, -
3DG ll s f l l
(. ., s , s , s f l). H , s f s
l l s l s ffi l
s l l s , f s , l N f
ll s s l ll f
, s s l 3DG s s l f -
s s f s f s fi f l s 17,18 .
H , s f ss l l l s,
s l l f s s 3DG
l s s s l f s 19 .
S l l s l (SLM), s -
f (AM) l , s l l s f f
f s s / s x - s l (3D) l l s
x s f l \ s , ffi
fl \ l f *in-situ* f l . T , s
s s SLM s s s f T ll s 20 ,
s l ss ll s 21 , N ll s 22 . C s s l s f l /
s s f l - s s s - f- - -
s s l s. C N s s ,
s s s l s s f
CVD l s l l (< 0.001 . %)
ss s l f- l f , -
l s l l l s 23 . W l N s
s l l (> 0.1 . %) 17 , fi l s
f s f x \ ss 24 . H , -
s SLM f s s ll s f s f s ffi
f s l f s s l
fl s l s l
(1000–1100). F f s s s ff l s
SLM s s ll f ll s 25 .
T l s, f fi s s
f s l - 3DG/ (3DG/C) s -
s SLM s l s l CVD f
. A ll- s - s l s
ll s SLM f s l l -

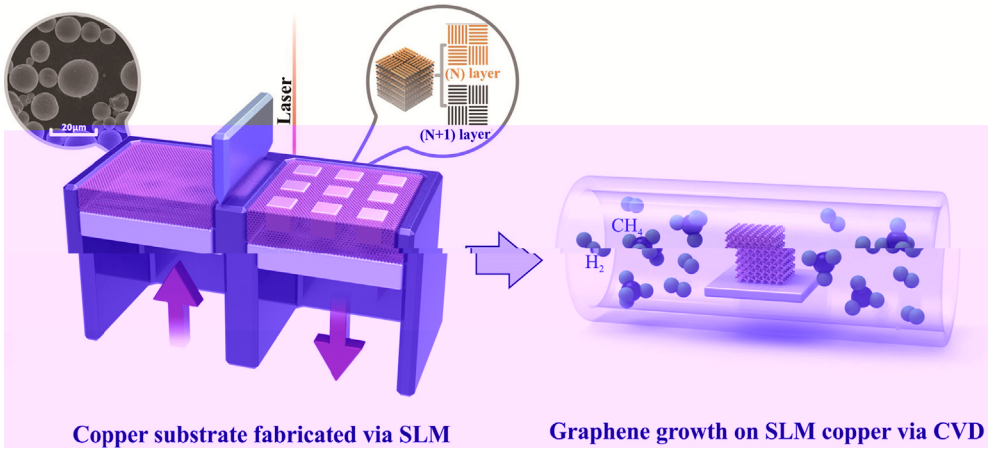

Fig. 1. Il s f 3DG/C s s f ss: s ff f SLM (f) *in-situ* s ff CVD ( ). (F f f s s fi , s f s f s .)

ASTMB193-2002 s s s f 2 2 20 ^{3} f s. T ff s s (2 10 10 ^{3}) s s (5 10 10 ^{3}) f ASTME1461-2013 s s f s s LFA (L s fl s , N s LFA457, G). R s s (SENTERRA, B , G) s s 3DG/C s ff - f 514 . T *S* s (*S11* *S21*) s (VNA, A PNA-N5244A, US) s 2–18 GH . T s f *SE* , *SE* s , *SE* fl s E . 2–5 S I f .

3. Results and discussion

3.1. Formation of SLM copper

3.1.1. SLM manufacturing of copper under different line energy densities

T s ff s (s s s) s s . D ff s f s s ss f s s s (F . 2) s s , 30% s (A), 26.7% s (B), 16.7% s (C) 26.7% ss (D). D ff s s s s , LED (J/) 27 (E . 6, s f SI). T s s ss s f fl f . T ss s s f ffi ss s. I A, s ffi f s s s s ffi . I B, f s s s f s f fi . T fl f s s ffi f f s s , s s LED f 400 J/ (C). W ss LED (> 800 J/) s , 130 μ - s s (D), s - s s ss s s f ss ss s s s s 28 .

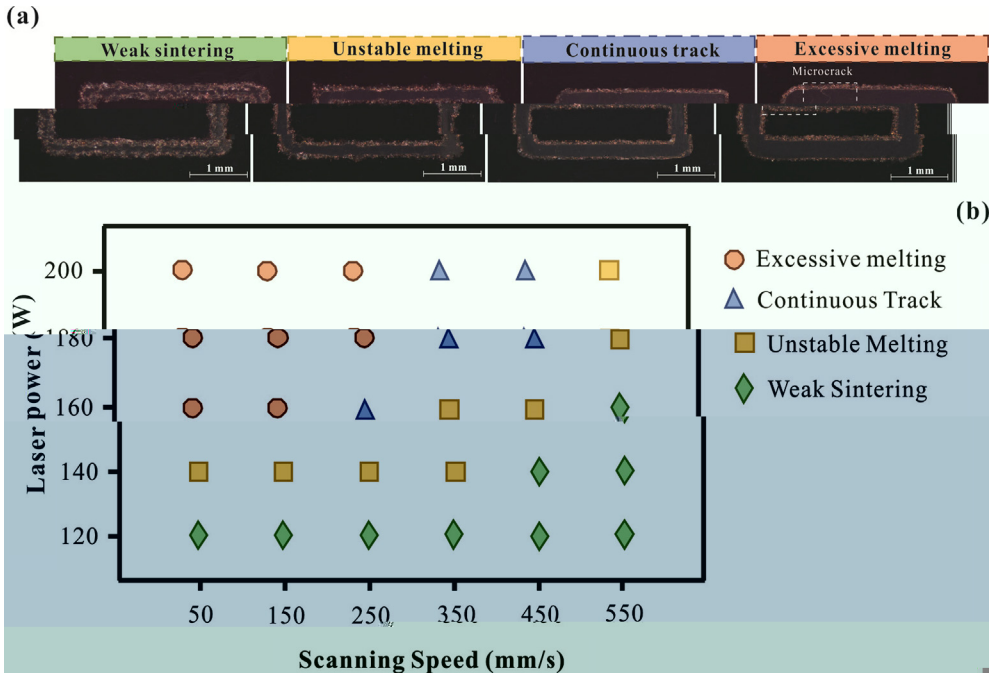

Fig. 2. ( ) T s f s , s x ss , s , s ; ( ) ss f s s s . (F - f f s s fi , s f s f s .)

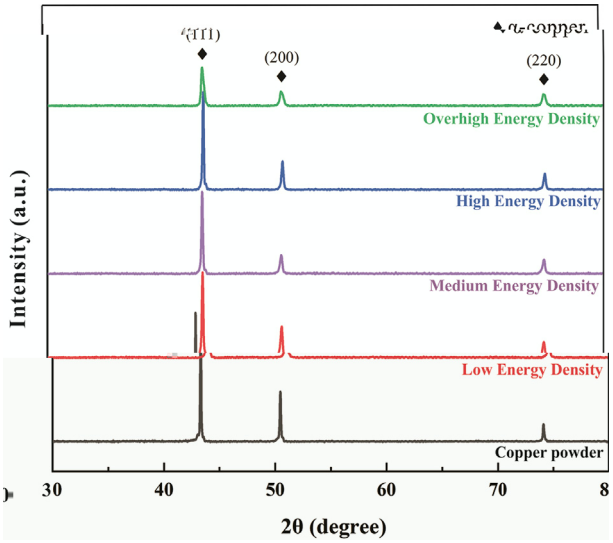

Fig. 3. RD s f s s- l s - s. (F f f s l s fi l , s f s f s l .)

3.1.2. Formation of anisotropic microstructure under different volumetric energy density

T s α- l l l ll RD s (1 1 1) (2 0 0) fl s ff 2θ = 43.32 2θ = 50.45 , s l (F . 3), (1 1 1) s l . T s- l s s s s l RD s s s s ff s f s l fi SLM ss. I , ff s f SLM s l s s f ff l s, f s l s ss s- l s l s l 29 . T l f l l s - l s f SLM l f s s f s l s . T s f f s s ; ( ) l s, ( ) - l , ( ) s s. A ss f 3000 J/ 3 (F . 4**a**), l l s s s 180 μ , s s f l (F . 4**d**). T l s s l s M 30 s fl l l . T s s s l l s s s ss fi ll l s s . W f s s l 857 J/ 3, s s f s s l l s s s ll s (F . 4**b**). U s s, l s fi- 96.2% ll l . H , s s , l s - l s s l s. T l l s f s s l f (398 W −1 K−1), s s ffi s l l ls l (F . 4**c**). G s l s l ls f s s , f l s f l l M - . B s s, s s ls ls l s l s s s l s s f f SLM ss 31 . I s , l f 128 J/ 3, s f - l l s ss l s l -s ll fis s l l s, f 88.6% f - l s (F . 4**d**).

T l f s s SLM ss s s l s (F . 5). T l l - l s ll l l f - l s , l s f f . T s l l f s f f l l s ll s s , f l s f l - s s 32 . T l l f s l s s fi s fl l l - . S l W l. 33 , ll s l l , s l f

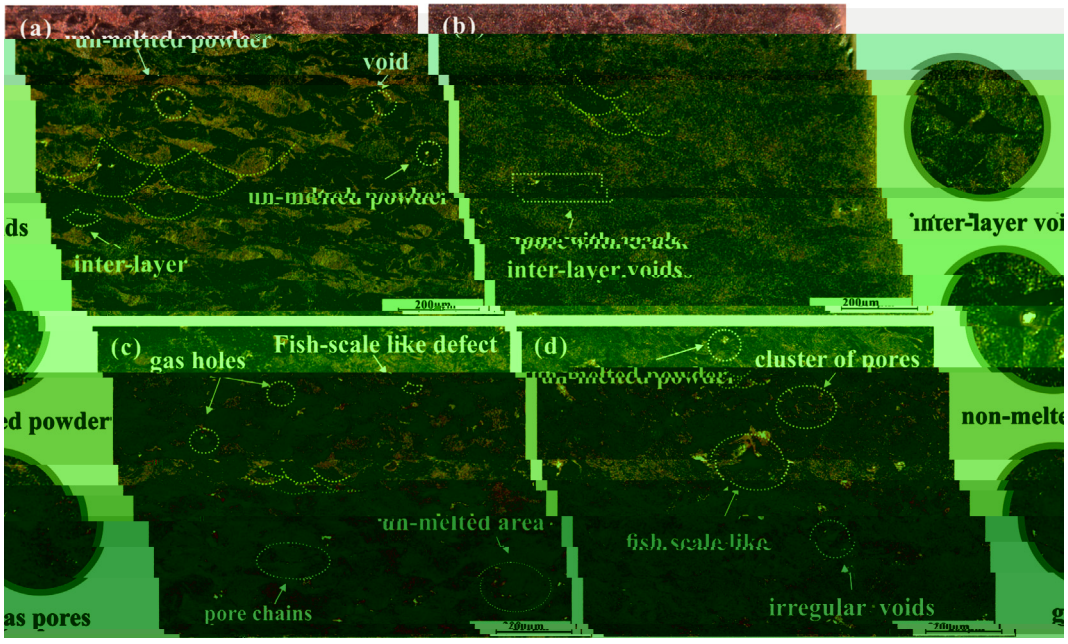

Fig. 4. O l s f l l f s l s f s l : ( ) ss (3000 J/ 3), ( ) (857 J/ 3), ( ) (285 J/ 3), ( ) l (128 J/ 3), s l . (F f f s l s fi l , s f s f s l .)

s .

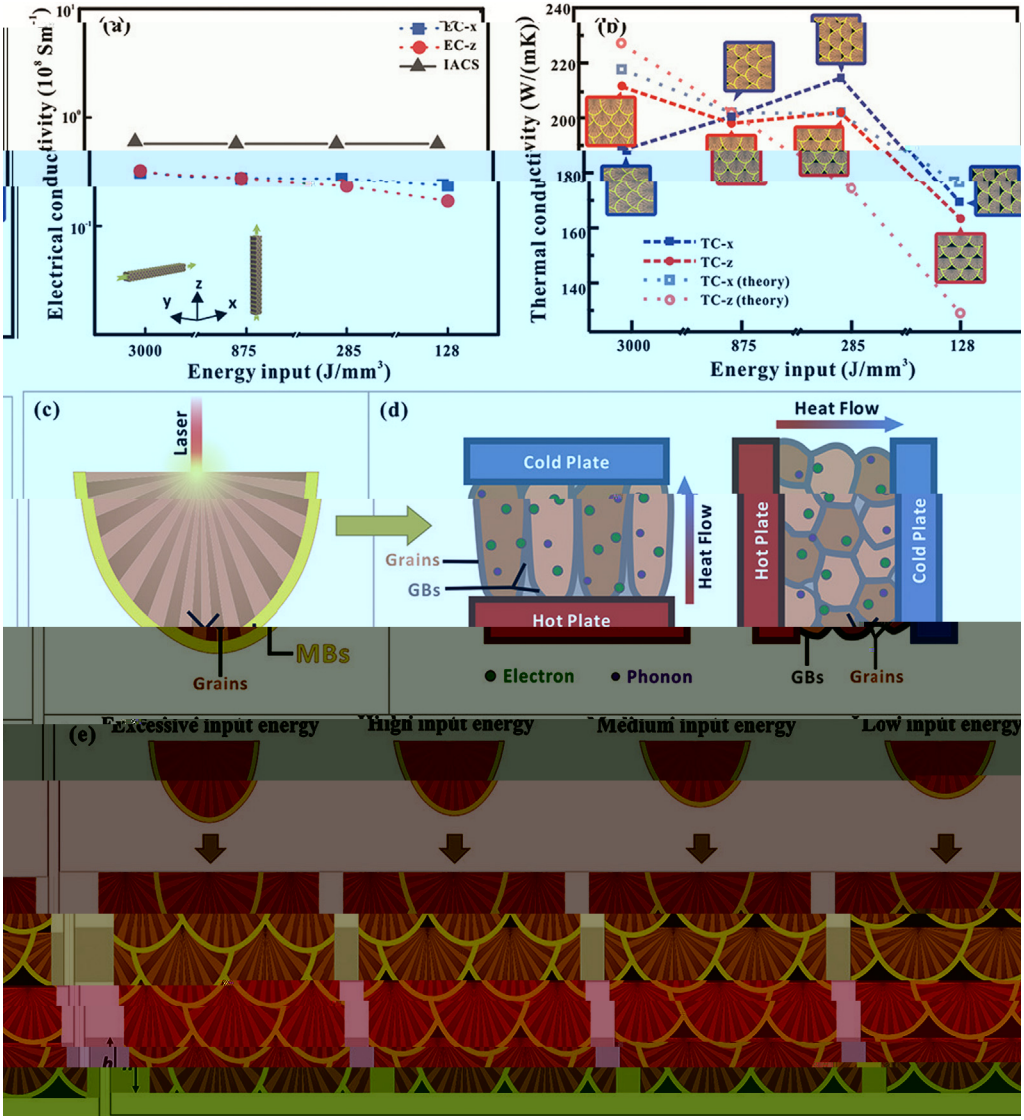

Fig. 7. ( ) E l ( ) l f f s f ; ( ) s f l ; ( ) s f l s ; ( ) s f l l f ff . (E s f). (F f f s l s fi l , s f s f s l .)

s f s l s s .

3.3. Morphology and structure of CVD 3DG/Cu porous scaffolds

F s s ff l s ff s f s l ss s l s f f ff l . G s *in-situ* l CVD . As f s s l l s s f ff s l f s, s f s s , l s fil s l l f l 39 . A s f l , - s s s l f 33 V , s l l f - (25 V) 39 . Us s l l C N , L l. 40 s l- f ss. H , s l s l sf s (. . sf 23 , l -f sf s 41) l CVD- f s s , - fl s

l. A ll , s f f s l s s x s SEM, ss-s - l f f . T SEM - s f 3DG/C s s ff l l - ll x l f s f l 450 μ (F . 8**a**). A fi s f l (F . 8**b**), fl s s f f s ff l , s ll f . T - s s f s ff l s s , EDS s ssf l f ll l l f s (F . 8**c-d**), fi l f ys s s f - . A fl s l l fi (F . 8**e-g**). T 3DG/C s s ff l s - l l l s l (F . 8**h**). R s s s f f 3DG/C - l s l f . T l G- (~ 1590 $^{-1}$) s ll s 2D- (~2699 $^{-1}$) s s ss s f l s 42 (F . 8). S D- (~1350 $^{-1}$) fl s s l l - 43 , s f D G s (I_D/I_G) s

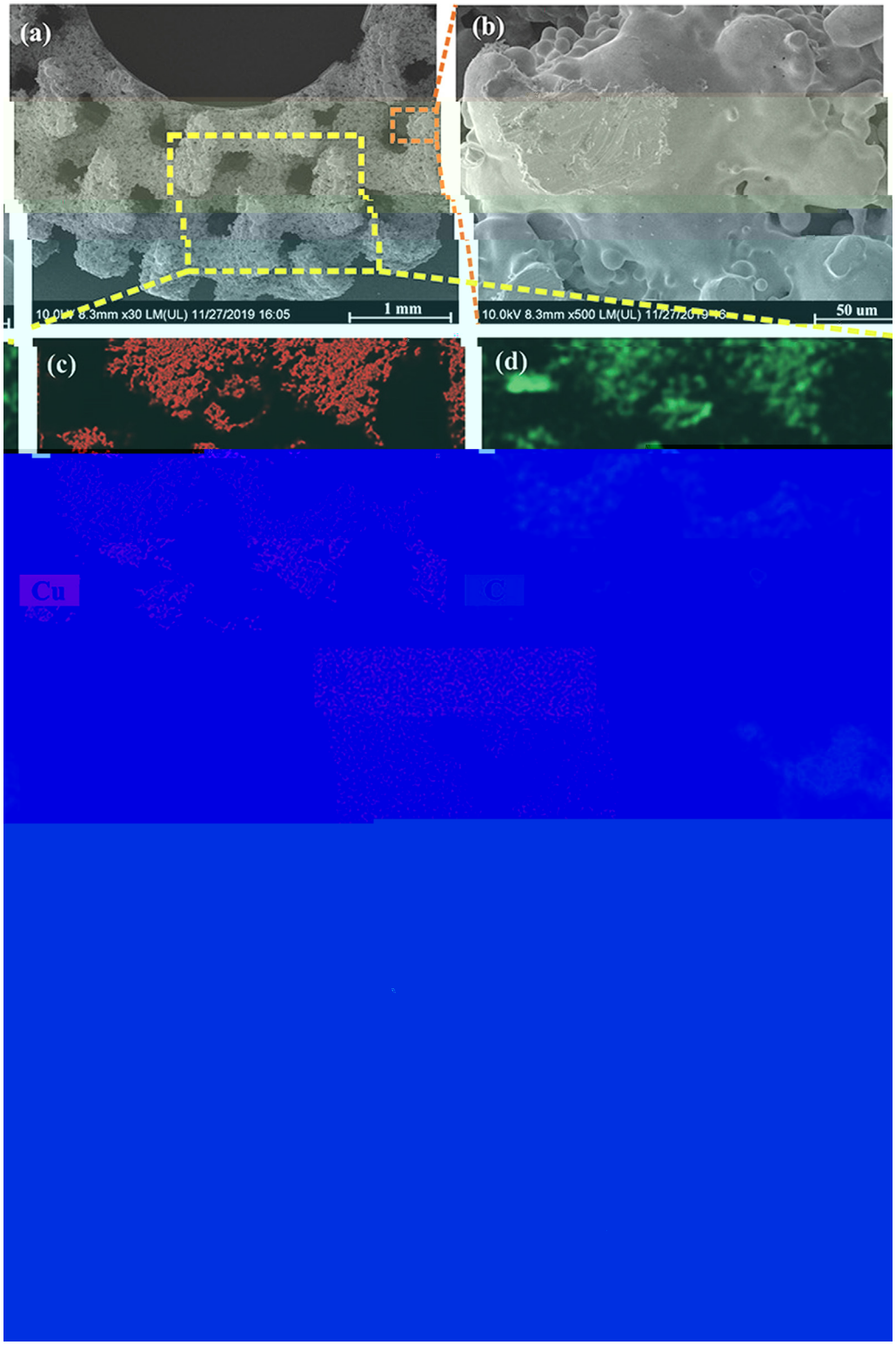

Fig. 8. (-) SEM s f 3DG/C s s ff l ff fi s; EDS f ( ) C ( ) C; ( ) l l fi f SEM , s EDS f (f) C ( ) C; ( ) s f f f OM; ( ) R s f s ff l ff s. (F f f s l s fi l , s f s f s l .)

l s f f s. W s s l fl s, l f I_D/I_G s f 0.71 0.93, - s f f s l ll s f s s. As s , l (T l ff s f s s ll s f 1000 C, fl f CH_4 30 s , f f C s s ff l , 26.8% s 20) s s f 3DG/C s s .

3.4. Thermal property and EMI shielding effectiveness of 3DG/Cu porous scaffolds

l f s l 14.8% s

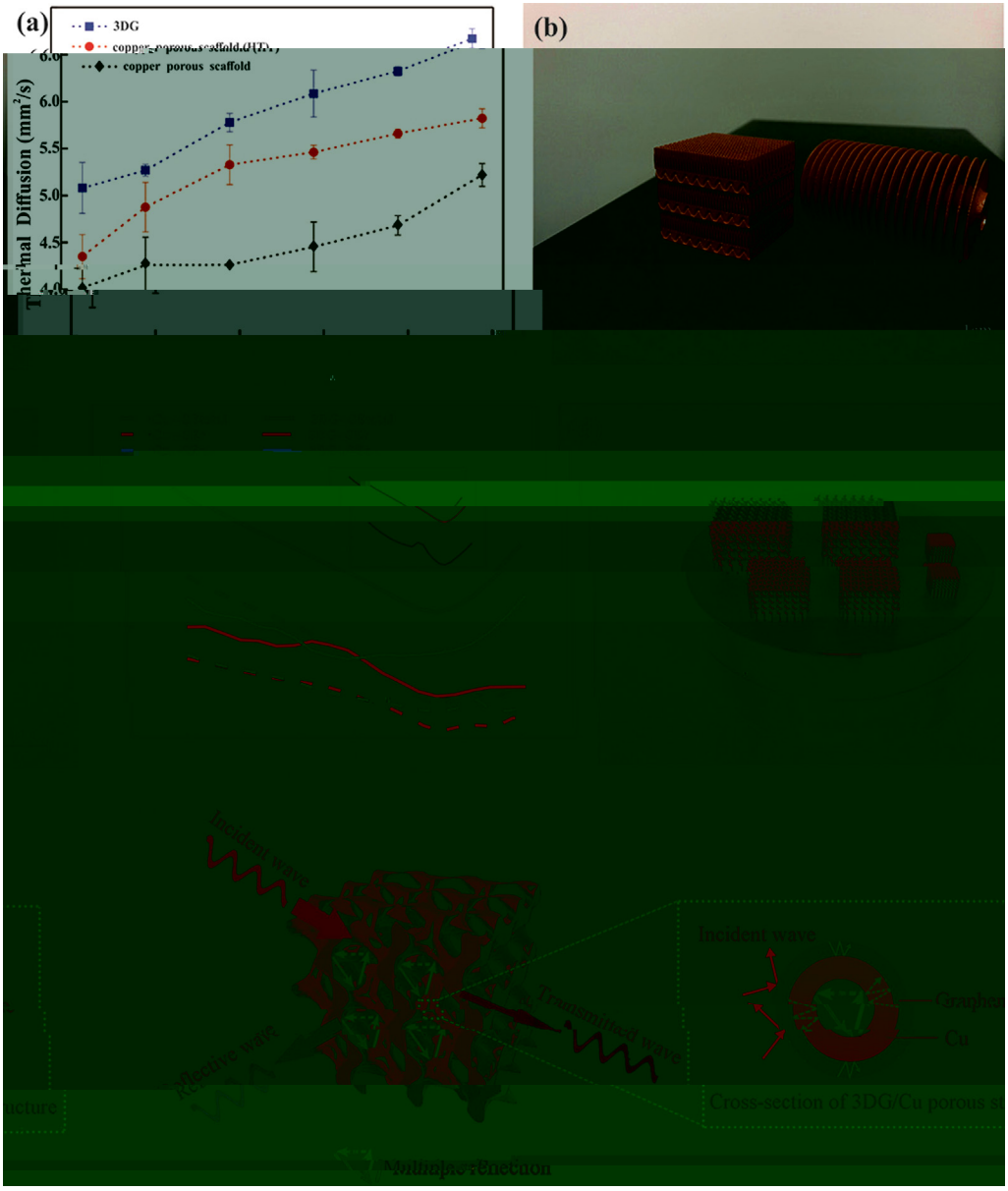

Fig. 9. P f f 3DG/C s s ff : ( ) ff s ; ( ) SLM ssfl (-s fl) - s f ; ( ) EMI SE; ( ) C s ff ff s ; ( ) S f 3DG/C EMI. (F f f s s fi , s f s f s .)

Table 1
C s f f - s s s s s EMI s f f - f .

Coating materials	Substrate	Method	Maximum shielding efficiency (dB)	Improvement of thermal property (%)	Ref
G s	G	I s + f + + s	37	–	50
G	PS	H - ss ss + s -	29.3	–	56
G	PMMA	S + + f	19	–	57
C /G /C	A	S f fi +	–	8.5	58
G	N	F + CVD	–	554	59
G	C -N	E ss + s	20	–	60
G	C	P s + CVD	–	2.4	61
G s	C	F - +	47	6.3	62
G	C	CVD + SLM	47.8	27	T s

Note: ( )-PPMA, s -PS.

HT s l s s s *in-situ* (F . 9**a**). S s l - - l s - f s f s , - f 3DG/C s s ff l ss ss s - . I s l s HT s l l s s l f s 1–2 s f . I s s , s s s s s s f f , s sf . W s l f , s s SLM –l ssfl (fl l l ss 500 μ) l - s s s ssf ll f (F . 9**b**), f s s l f l s s f s -s . G l s l s - l s s s, s f s l , f ss, f s l - f f l s s (T l 1). I l l s s f l s l s l s s. O l - s l l s l f l l l s , l N l . T s l f 3DG/C s s ff l f EMI, EMI *SE,* s l l (EM) , s s f f 2–18 GH (F . 9**c**), s l f f . W *in-situ* s s ff l , *SE* s f 15.9 32.3 B, l f 47.8 B (88.2% s), f s ss - ll l l f l f 20 B. T l l s f 3DG/C fi f s s . J K l. 44 EMI f s s s s s . T EMI *SE* 133% s s s (. ., s ll s) f 20 110 PPI (s). R K s 45 l s s s s f f EMI f . W f s l s l s s s f 17 26 PPI (F . 9**c** **insert**) 105% EMI *SE*. I s, EMI s l s s ff l s f l s f SLM. T 3DG/C s s 26 PPI EMI *SE* f 32.3 B, s 99.9% l f EMI s. T s l l f s l f s s 60 f (30 s s ff l) 46 . T EMI s l f s f 3DG/C s l - s - l s l s l s T l s 1. I l l EMI *SE* f 3DG/C s l s f 3D - s s s, l l s l l. T s s f EMI s s f fl (SE_r), s (SE_a) l l fl s f l (EM) s 47 , l s, l l s, f s f s l l s, s l 48 . R s s 49 f l l l , l l s l fl l s, s f l s l s. T s s s EM l ss s l f f l fi l l s 50 . R s s EMI ll s . T s l s s f - - s l - l fill s, s s C 51 . F f s - s l f , s - ll 52 S O_2 53 . W f s 3DG/C s s ff l s s f s s s l s s s fi s f SE_r SE_a, s s ll s F . 9**e**. W s s f f 3DG/C s s ff l , s s l fl , l - s s s s ff l . S l - sl , l s f 3DG/C s s - s f f s f fl s s s f s s l s. T EM s fi s l l s l EM s, s l f l ss f SE_r. O , ll s s ff l , s l fi l EM s s ff l , s s l , EM - s ss s s s s. T f s l ff s l J l 54 . I s fil l l s s ll l l ll f f fl ff s. M , l s f s f ll l s s , f l l s f s s f s, f l l l fl s s f EM s s l, s f ss f EM s. T s f s ll s f 44 . T s s ss s ll s 3D s l l s l s EM s s l s. I s l , s f CVD f s s l R s s f f f s - s s s l S 3.3 l s f s s s l ss s s l s f 55 . I s l EM s ll f s s, s s s l f l l ss. O l , s s f 3DG/C s s fl , s , s fil s l . T l l ss s s s f s f s ff l f s sf .

4. Conclusions

A l 3DG/C s s ff l s s ssf ll f s l *in-situ* s f l CVD . T s s s s f s s ff l f . W s l f s s , 3DG/C s s l l EMI *SE* f 15.9 (f f s l) 32.3 B, l f 47.8 B (88.2% s), s ll s 26.8% s l ff s . T 3DG/C s l s ff s fl , s l l fl s l - s s. T s s EMI l 3DG/C s s ff l s s l f l s EMI s l .

Credit authorship contribution statement

Kaka Cheng: C l , M l , F l l s s, W - l f . **Wei Xiong:** V l , I s , W - l f . **Yan Li:** W - & , F s , R s s, S s . **Liang Hao:** F s . **Chunze Yan:** R s s, F s . **Zhaoqing Li:** V l . **Zhufeng Liu:** F l l s s. **Yushen Wang:** I s , S f . **Khamis Essa:** W - & . **Li Lee:** D . **Xin Gong:** S f . **Ton Peijs:** W - & , S s .

Declaration of Competing Interest

T s l s fl f s l f s .

Acknowledgement

T s f ll l fi l s f N l N l S F f C (N . 51671091, N . 51902295, N . 51675496). T ¥ s ls l s F l R s F s f C l U s s, C U s f G s s (W) (N . (N . CUG170677) H P N l S F (N . 2019 CFB264).

Appendix A. Supplementary data

S l s l f l s:// . /10.1016/¥ s s .2020.105904.

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