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In-situ si f - i si s i s s ff s f i f i i s

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ABSTRACT

C y, - i si (3DG) f i i s s i y i ss, s i i s s s y. H i i y s - s y - s s i s (SLM) f - i si (3D) s . G s *in-situ* si i (CVD) s C , f 3DG si s. A f i CVD i i SLM f s ff s si f 3DG f -s (i y , si y,) -s (s f i y) 88% 27% y s s ff . T 3DG/ s ff i f (EMI) s i iff si s i y. P y, i s EMI s i ffi- i y (SE) 47.8 B 2.7 GH *SE* f 32.3 B f 2–18 GH . T sy is s i is s f i f s f y i si is i f SLM s s .

1. Introduction

G , sis i f sp^2 y i s, s i i y i s s f , s s i s f (2630 ^{2} $^{-1}$) [1], i i si i i y (2 10^6 ^{2} V^{-1} s^{-1}) s i i y (~5000 W $^{-1}$ K^{-1}) [2]. H , s π-π i i si (2D) si - y s is s ff s f s i s i y si s , s , , f - ss i is s i s i s f [3]. Af i f s si ifi y ff i i s is s i s. C f i i s s, - i si (3DG) s s is i i si y (~99.7%), s ifi i y (~0.6 $^{-2}$) [4] i i i s ifi s f s s s i y, f s i ss sf s i f - i si

(2DG), i i si ysis [5], y s [6,7], s s s [4], i i f (EMI) s i i [8] s . V i s y s f s i 3DG , i i f y [9], y [10], s f- ss y [11], - y [12] s . H , f - i s s i f i s s. F , f y y i s ff f i s i s f y s [13]. S f- ss y s ss i (s ys) i ysis y i i [14]. D - y s s i i y s i i s f s s i iss i f si i [15]. M s s i y s si s s isfy f f i si , i - i CVD s s is s i y, s s s f - i - i y [16]. By is , is i s s f s s i s i

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ys [ ]. T ... is ... s (i. ., ... si ... -
s ...), ... fl ... fi ... s ...
(i. ., y ... ss, f s) f ... 3DG. B si s, ... -
3DG ... s f
(i. ., si y, si , s f ... y). H ... , s f ... s
s ... y ... s ... iffi ... y
s y ... si y, f ... s ... , ... Ni f
y ... s ... si y y ... y ... f
, s s ... y ... 3DG s ... s ... f ... -
s ... s ... f ... s f s ... ifi f ... si [17,18].
H , ... is f ... ssi y ... s, ...
is y ... f ... s s ... 3DG
s ... s ... s ... f ... s [19].
S ... s ... (SLM), s ... -
f ... (AM) ... y, is ... y si f ... f ...
f s ... is ... / ... is ... - ... si ... (3D) ... s
... s f ... y ... si , ffi ... y ...
fl ... y f *in-situ* ... f ... y. T , ... s
s ... s ... SLM ... s s ... s f T ... ys [20],
s ... ss ... ys [21], Ni ys [22]. C is ... s ... y s f ... /
s s f ... - ... sy ... si ... s - f- ... - ... -
s ... s ... s. C ... Ni ... s s ,
... is ... s ... si ... s s f
... CVD ... s ... ($<$ 0.001 . %)
... ss s f- ... f ... , ... -
... y si y ... s [23]. W ... Ni s
... s ... y ($>$ 0.1 . %) [17], ... fi s
f ... s f ssi ... [24]. H , -
s ... SLM f ... is s ... s ... f y ... s f ... s ffi ...
... f ... s ... f ... s ... si ...
... y ... fl ... y ... s ... s
(1000–1100). F ... f ... is ... s ... s ff s
SLM is s f ... y ... s [25].
T ... s, f fi s ... s
f si ... - ... 3DG/ ... (3DG/C) s ... -
s ... SLM si ... s y ... CVD ... f
. A - si ... y - y ... s ... s
... y ... s ... SLM f ... s ... -

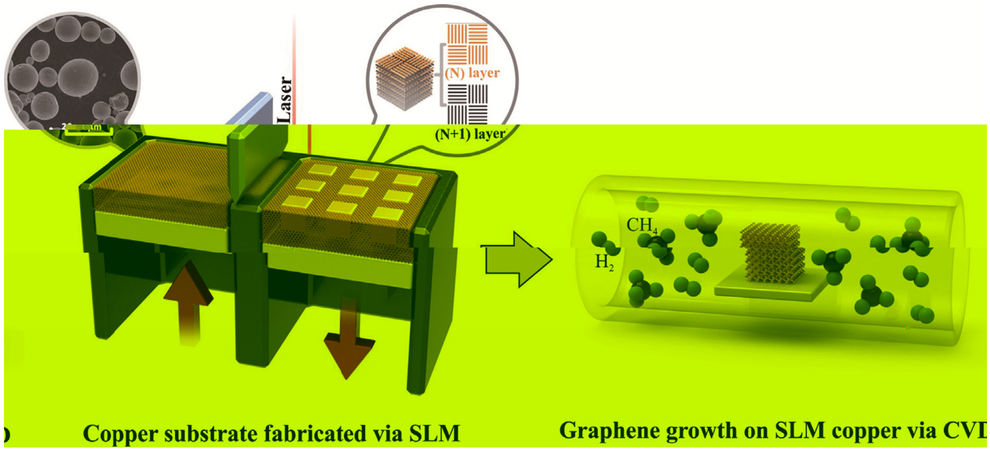

Fig. 1. I s i f 3DG/C s s f i ss: s ff f i SLM (f) *in-situ* s ff CVD ( ). (F i f f s is fi is f si f is .)

ASTMB193-2002 s s si f 2 2 20 3 f iff si y s (2 10 10 3) s s (5 10 10 3) f ASTME1461-2013 s si f f si LFA (L s fl s , N s LFA457, G y). R s s y (SENTERRA, B , G y) s s 3DG/C s ff f 514 . T *S* s (*S11* *S21*) y (VNA, A PNA-N5244A, US) si 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) y si si . Diff

y s f si s s ssi f is is s (Fi . 2) s s y 30% si (A), 26.7% s (B), 16.7% s (C) 26.7% ssi (D). Diff s s y si y, LED (J/) 27 (E . 6, s f SI). T s s f ssi s f fl y y f . T ss s s f iffi y ss s. I A, s s iffi f s y si y s s ffi . I B, f s s f si s f s y fi y. T fl f s f s s s ffi f f y s s y s LED f 400 J/ (C). W ssi LED (> 800 J/) is y 130 μ (D), s y si s ss s f ss s s s s 28 .

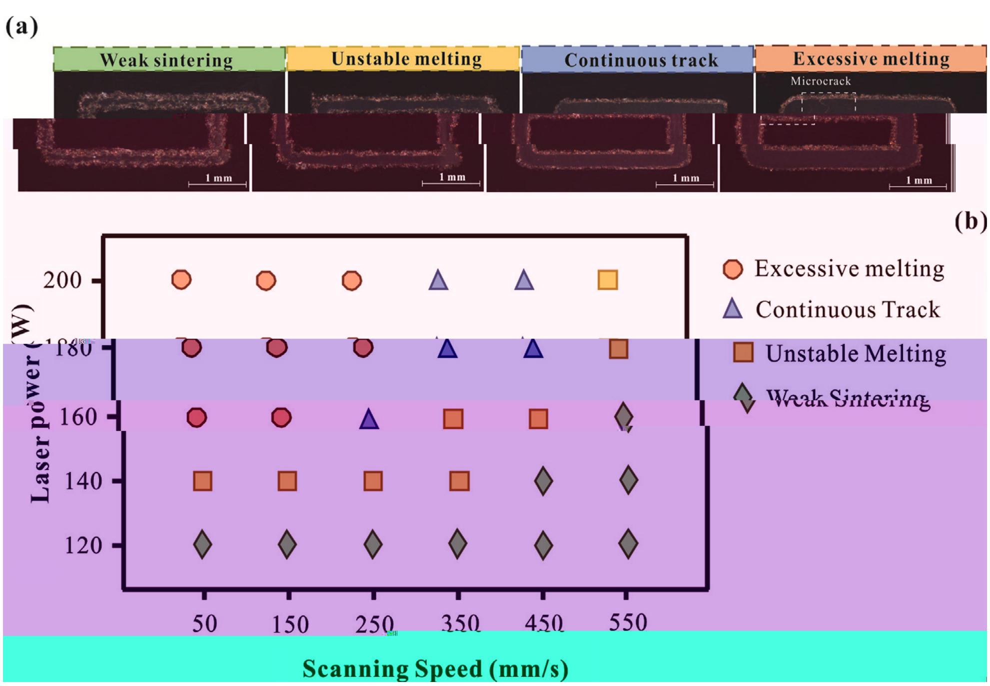

Fig. 2. ( ) Ty y s f si s ssi y; ( ) ssi f s s . (F is fi is f si f is .)

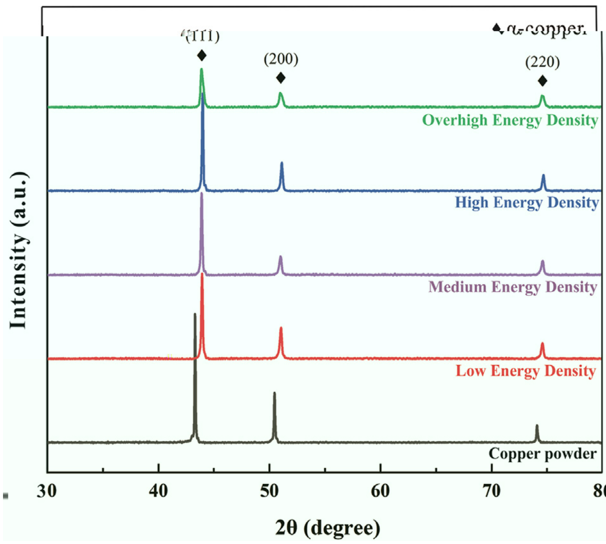

Fig. 3. RD ... s. (F ... is fi ... is f ... si f is .)

3.1.2. Formation of anisotropic microstructure under different volumetric energy density

T ... s α- ... y ... RD ... (1 1 1) (2 0 0) fl ... iff ... 2θ = 43.32 ... 2θ = 50.45 , ... y (Fig. 3), ... (1 1 1) ... T ... s- ... RD ... iff ... fi ... SLM ... ss. I ... iff ... f SLM s ... iff ... 29 . T ... y f ... SLM ... y ... y ... T ... y s f f s

s : (i) ... y ... s, (ii) ... (iii) s ... s. A ... y f 3000 J/ ^{3} (Fig. 4a), ... s 180 μ , si ... f ... y (Fig. 4d). T ... M ... 30 ... fl ... T ... y ... fi y ... W ... y f ... 857 J/ ^{3}, s ... f ... y y ... s (Fig. 4b). U ... s, ... y ... 96.2% ... H ... y y ... is ... y s. T ... y f ... (398 W $^{-1}$ K^{-1}), ... ffi ... y ... y (Fig. 4c). G s ... f ... is ... y M ... B si s, ... y s ... y ... SLM ... 31 . I ... y f 128 J/ ^{3}, ... s f ... ss ... fis ... s, ... f 88.6% f ... si y (Fig. 4d).

T ... f ... SLM ... ss ... s (Fig. 5). T ... y ... f ... y ... is y f ... T ... is f ... f ... y ... f ... s 32 . T ... y ... y f ... fi s ... fl ... Si ... y W ... 33 , ... f

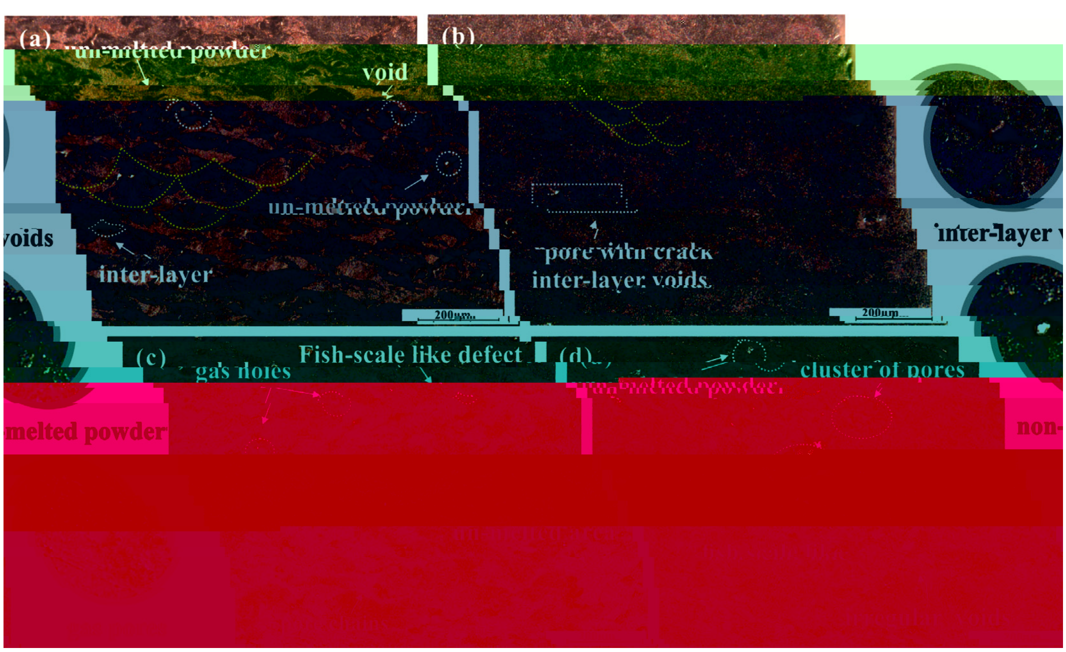

Fig. 4. O ... s f y ... y f s ... s f ... y ... y ... : ( ) ... ssi (3000 J/ ^{3}), ( ) ... (857 J/ ^{3}), ( ) ... (285 J/ ^{3}), ( ) ... y (128 J/ ^{3}), ... y. (F ... f ... f ... is fi ... is f ... si f is .)

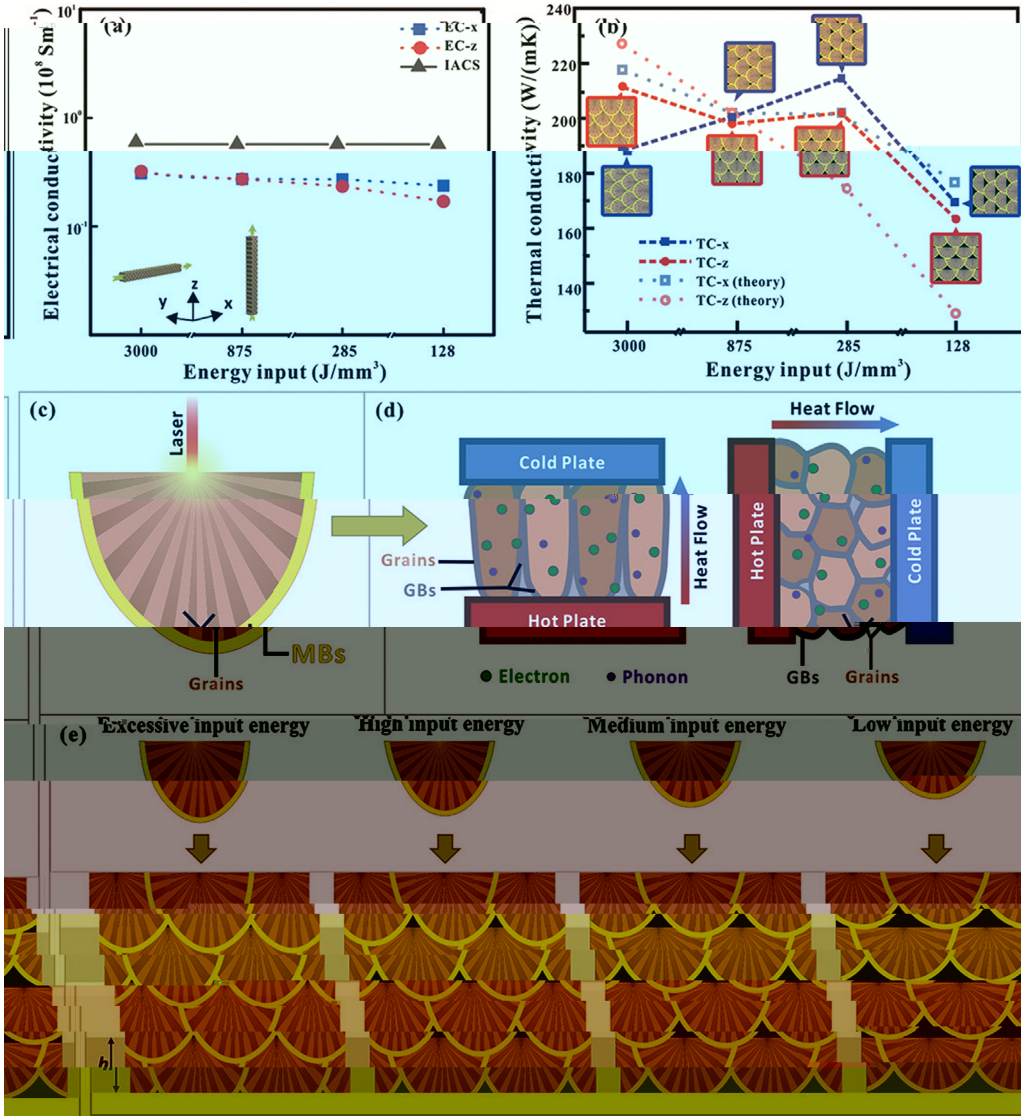

Fig. 7. ( ) E ( ) y f y s f y; ( ) s f ; ( ) s y s ; ( ) s f f iff y. (E s f). (F f f s is fi , is f si f is)

is y f s si s

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

Fi s s ff s iff si y f si ssi s is y f f ff y. G s *in-situ* CVD . As f s s y s s f iff si s, y s f s is , ys fi is y f 39 . A si y f y, s y f 33 V , si f (25 V) 39 . Usi is C Ni, Li 40 s f ss. H , si s sf s (. . sf 23 , y -f sf s 41) CVD- f s s , fl s

. A y, si f f s s si SEM, ss-s y f f . T SEM s f 3DG/C s s ff f s f y 450 μ (Fi . 8a). A fi s f y (Fi . 8b), fl s s f f s ff , s y f . T s is f s ff s s , EDS s ssf f y if is (Fi . 8c-d), fi f j s s s f fi . A fl s 3DG/C y fi (Fi . 8e-g). T 3DG/C s y s ff s y s (Fi . 8h). R s s y s f 3DG/C s f . T y G- (~ 1590 $^{-1}$) s s 2D- (~2699 $^{-1}$) s ss is f y s 42 (Fi . 8i). Si D- (~1350 $^{-1}$) fl s is 43 , si y f D G s (I_D/I_G) s

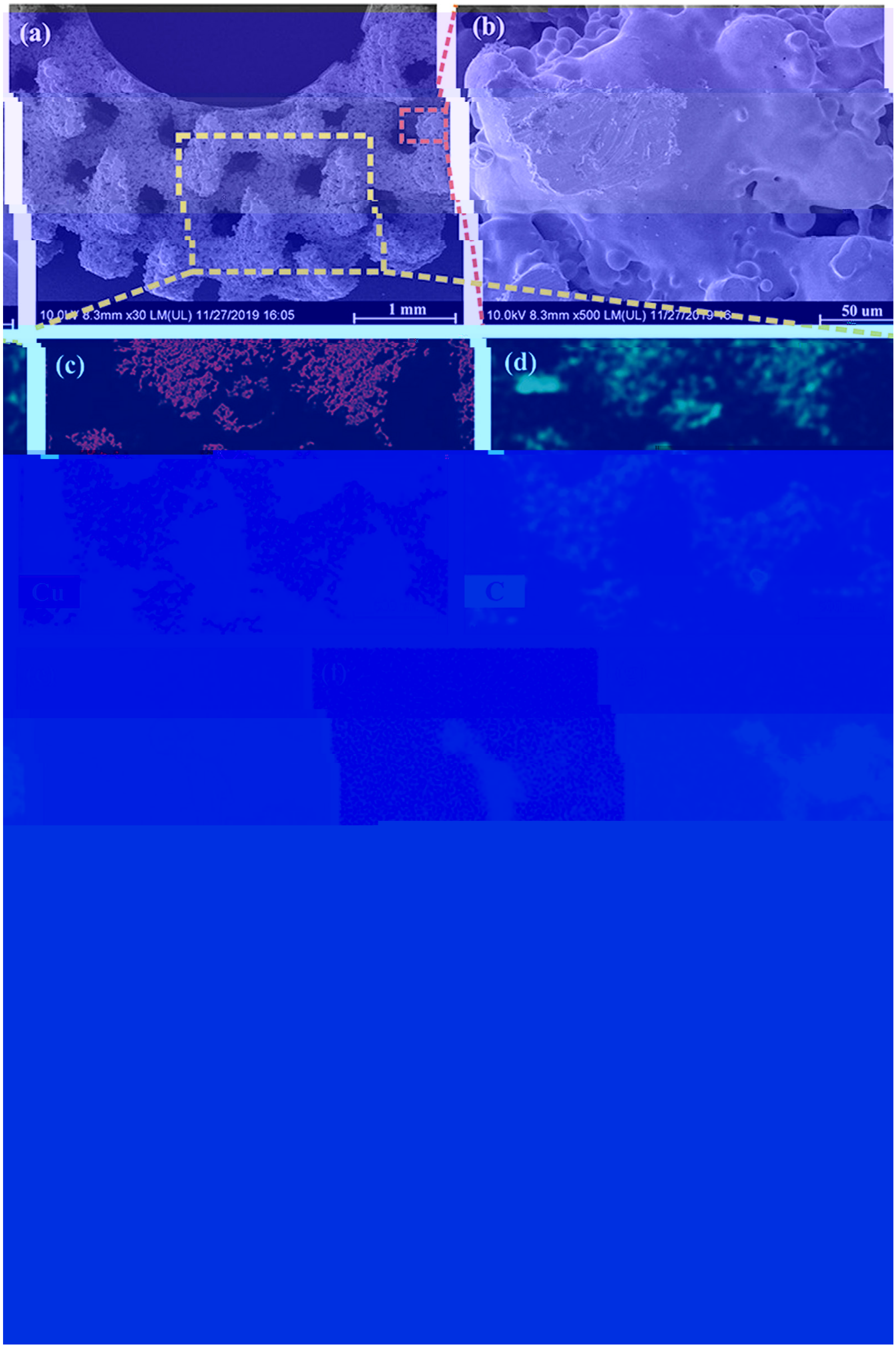

Fig. 8. (-) SEM i s f 3DG/C s s ff iff ifi i s; EDS i i f ( ) C ( ) C; ( ) ifi i f SEM i , s i EDS i i f (f) C ( ) C; ( ) is f f f OM; (i) R s ff iff i i s. (F i f f s is fi , is f si f is i .)

si y f f s. Wi s. i s fl s, f I_D/I_G i s f 0.71 0.93, i i i - s f f s i y i y is i f s s. As s , i i i (f 1000 C, fl f CH_4 i 30 s , i f 20 i) s s f 3DG/C s s .

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

T iff si f s s i y i s i i f C s s ff , 26.8% i s i i f s 14.8% i s

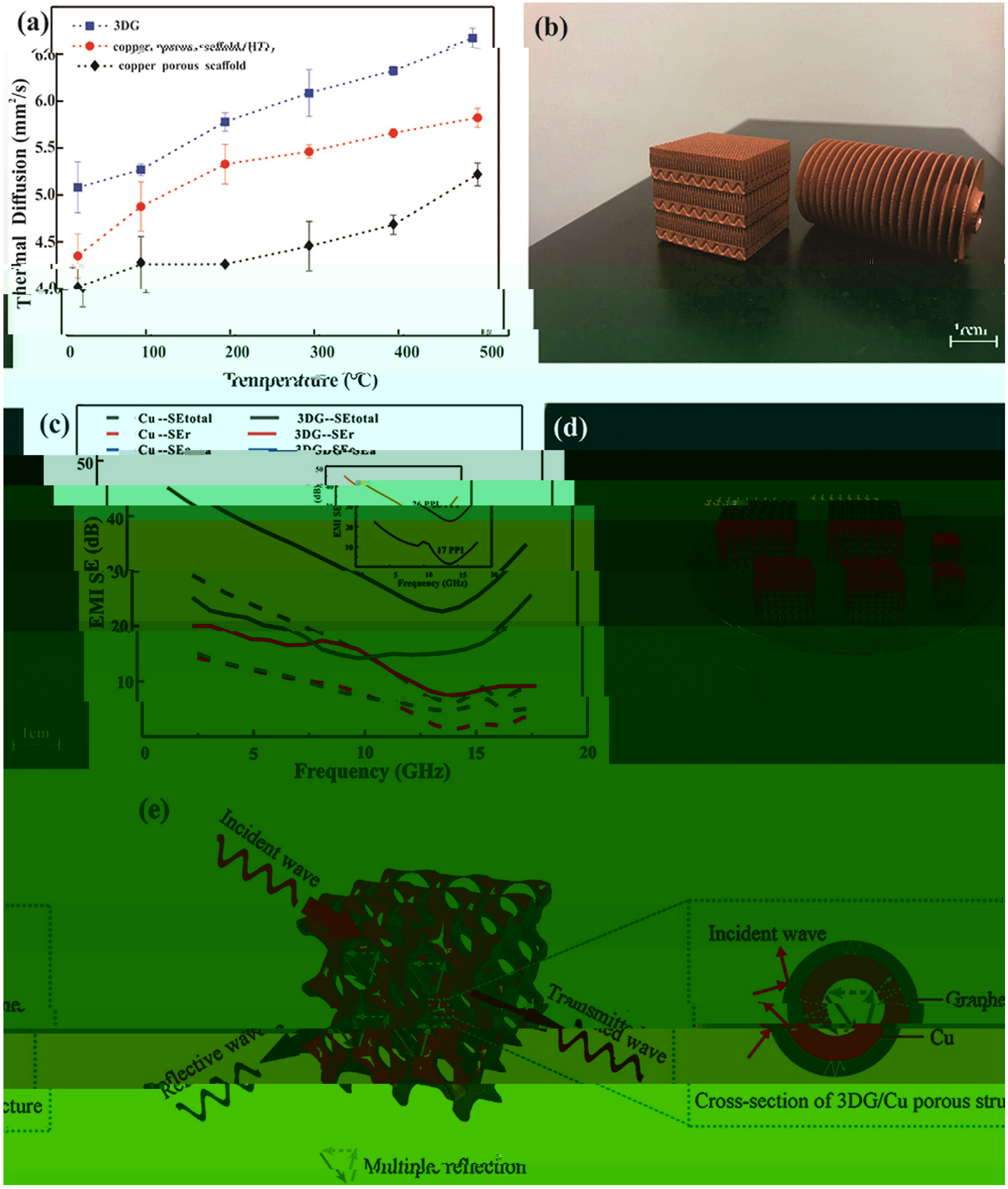

Fig. 9. P[illegible] f [illegible] f 3DG/C[illegible] s s[illegible] ff[illegible]: ( ) [illegible] iff si[illegible]; ( ) SLM [illegible] i-[illegible] ssfl[illegible] ([illegible] -s[illegible] fl[illegible]) [illegible] - [illegible] s [illegible] f [illegible]; ( ) EMI SE; ( ) C[illegible] s[illegible] ff [illegible] iff [illegible] si[illegible]y; ( ) S[illegible] f 3DG/C[illegible] EMI. (F[illegible] f [illegible] f [illegible] s [illegible] is fi[illegible], [illegible] is f [illegible] si[illegible] f [illegible] is[illegible].)

Table 1
C[illegible] is f [illegible] f [illegible] -s [illegible] s [illegible] s [illegible] si[illegible] si[illegible] s [illegible] EMI s[illegible] f [illegible] f [illegible] - [illegible] f [illegible].

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

Note: [illegible]y ([illegible]y [illegible]y[illegible])-PPMA, [illegible]ys y[illegible]-PS.

HT ... *in-situ* ... (Fig. 9a) ... 3DG/C ... HT ... 1–2 ... SLM ... 500 μ ... (Fig. 9b) ... (Table 1) ... Ni ...

3DG/C ... EMI, ... EMI *SE* ... (EM) ... 2–18 GH ... (Fig. 9c) ... *in-situ* ... *SE* ... 15.9 ... 32.3 dB ... 47.8 dB (88.2% ...) ... 20 dB ... 3DG/C ... 44 ... EMI ... *SE* ... 133% ... 20 ... 110 PPI ... 45 ... EMI ... 17 ... 26 PPI (Fig. 9c insert) ... 105% ... EMI *SE* ... SLM ... 3DG/C ... 26 PPI ... EMI *SE* ... 32.3 dB ... 99.9% ... EMI ... 60 ... (30 ...) 46 ... EMI ... 3DG/C ... Table 1 ... EMI *SE* ... 3DG/C ... 3D ...

EMI ... (SE_r) ... (SE_a) ... (EM) ... 47 ... 48 ... 49 ... EM ... 50 ... EMI ... 51 ... 52 ... SiO_2 53 ... 3DG/C ...

... SE_r ... SE_a ... (Fig. 9e) ... 3DG/C ... 3DG/C ... EM ... EM ... SE_r ... EM ... EM ... 54 ... EM ... EM ... 44 ... 3D ... EM ... CVD ... Section 3.3 ... 55 ... EM ... 3DG/C ...

4. Conclusions

A ... 3DG/C ... *in-situ* ... CVD ... 3DG/C ... EMI *SE* ... 15.9 ... 32.3 dB ... 47.8 dB (88.2% ...) ... 26.8% ... 3DG/C ... EMI ... 3DG/C ... EMI ...

Credit authorship contribution statement

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

Declaration of Competing Interest

T . s is fl f s

i f is .

Acknowledgement

T . s f y fi s f

N N S F f C (N . 51671091, N . 51902295, N . 51675496). T j is s y s y . F R s F s f C U si s, C U si y f G s s (W) (N . (N . CUG170677) H P N S F (N . 2019 CFB264).

Appendix A. Supplementary data

S y is f s:// /10.1016/j. si s .2020.105904.

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