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In-situ [illegible]

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ABSTRACT

[illegible] (3DG) [illegible] (SLM) [illegible] (3D) [illegible] *in-situ* [illegible] (CVD) [illegible] 3DG [illegible] CVD [illegible] SLM [illegible] 3DG [illegible] 88% [illegible] 27% [illegible] 3DG/ [illegible] (EMI) [illegible] EMI [illegible] (*SE*) [illegible] 47.8 [illegible] 2.7 GH[illegible] *SE* [illegible] 32.3 [illegible] 2–18 GH[illegible] SLM [illegible]

1. Introduction

[illegible] *sp*[2] [illegible] (2630 [illegible]) [1], [illegible] (2 [illegible] 10^5 [illegible] V^{-1} s^{-1}) [illegible] (~5000 W [illegible] K^{-1}) [2]. [illegible] π-π [illegible] (2D) [illegible] [3]. [illegible] (3DG) [illegible] (~99.7%), [illegible] (~0.6 [illegible] $^{-2}$) [4] [illegible]

(2DG), [illegible] [5], [illegible] [6,7], [illegible] [4], [illegible] (EMI) [illegible] [8] [illegible] 3DG [illegible] [9], [illegible] [10], [illegible] [11], [illegible] [12] [illegible] [13]. [illegible] [14]. [illegible] [15]. [illegible] CVD [illegible] [16]. By [illegible]

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t lyst. T i es i t isti s (i. ., esiti i - st t), t t i i fl t fi l i est t (i. ., l y t i ss, f ts) f t 3DG. B si s, t - t 3DG ill i it t ti s f t t l t l t (i. ., esity, si , s f lity). H , est f t s t l t l t s y ti l t s iffi lty i sly l ti esity, f i st , t i l Ni f lly s t esity y ly t ll f i t t t, t s s tly t i 3DG s s t l f - s i i es i f t s f s ifi f ti l si 17,18]. H , it is f ssity t l t l t l t s, i is ly i l t f te i s ts t i 3DG it t l st t s st l f s 19].

S l ti l s lti (SLM), s i ti iti - f t i (AM) t l y, is ti l ly si f t f i ti f s isti t / is t - i si l (3D) t l t l t s it t t s f l ity i si , ffi i y i ti fl i ility f *in-situ* f t i ility. T t , s s s t SLM s st t s f Ti lleys 20], st i l ss lleys 21], Ni lleys 22]. C is t est i ly s f il/ s st t f l - sy t si i st t - f-t - t - s i st i l s. C it Ni t s st t , is s si l s st t f t i CVD t t l s t ti l l (< 0.001 t. %) t ss s lf-li iti f , i t t t i - lity si l l y it l s 23]. W il Ni s i s l ility (> 0.1 t. %) 17], t i fil s t t f s f ssi i it ti 24]. H , - s i SLM f is still i its i f y s f i s ffi i t ti f s lti i f its i t i si i t l ti ity fl ti ity t s l s l t (1000–1100). F i ti f is s s ff l s i SLM is still f i y ll s 25].

T li it ti s, f t fi st ti es f si l tt - t 3DG/ (3DG/C) st - t s i SLM si lt sly i i ti it CVD t f . A ll- si y i -ty s t l t s i iti lly i sti t i SLM f i est t l l ti t -

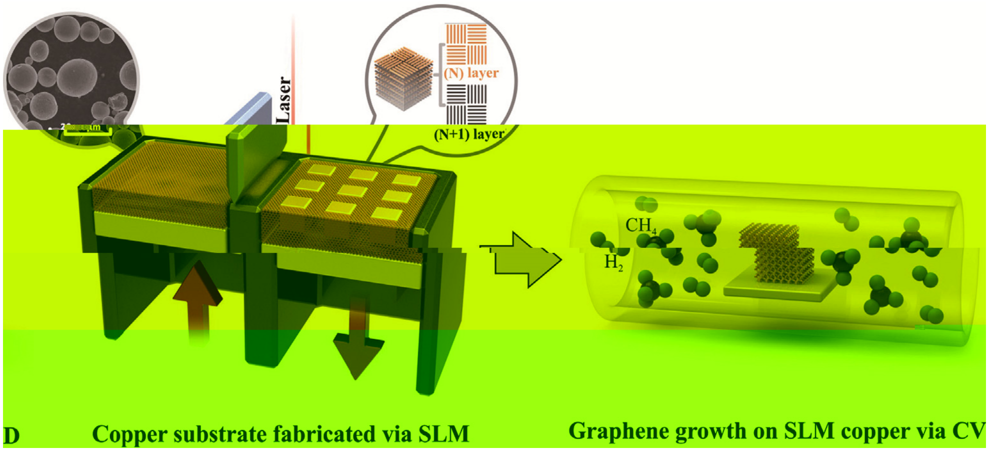

Fig. 1. Ill st tio of t 3DG/C o o s st t f i tio o ss: o s ffol f i t i SLM (l ft) *in-situ* o t o t o s ffol i CVD (i t). (Fo i t t tio of t f s to olo i t is fi l , t is f to t sio of t is ti l .)

ASTMB193-2002 i ts it s l si of 2 2 20 ^{3} f o ot o i o t l ti l o i t tio s. T t l iff si ity s t o t i (2 10 10 ^{3}) o o s st t (5 10 10 ^{3}) follo ASTME1461-2013 it s l si of t fo tio t o o i t tio s si t LFA (L s fl s t o , N t s LFA457, G y). R s t os o y (SENTERRA, B , G y) s s to t i t 3DG/C s ffol it - it tio l t of 514 . T *S* t s (*S11* *S21*) s it to t o ly (VNA, A il t PNA-N5244A, US) si t o i l t o i 2–18 GH . T l s of SE_{tot} l, *SE* so tio , *SE* fl tio t i s E . 2–5 i t S o ti I fo tio .

3. Results and discussion

3.1. Formation of SLM copper

3.1.1. SLM manufacturing of copper under different line energy densities

T ost ff ti t s (l s o s i s) li i ily i sti t i si l t i . Diff t ty s of si l t s o s t o ssi i o o l fo ot i i i to fo isti is i o s (Fi . 2) s o t lti t s lity, i l i 30% si t i o (A), 26.7% st l lti o (B), 16.7% o ti o s t o (C) 26.7% ssi lti o (D). Diff t o s s t i s li y sity, LED (J/) 27] (E . 6, l s f to SI). T s l t l s i o ssi o ti i tio o to o o t ll s of i fl ti ity t l o ti ity of o . T l ss o ti o s t lso i i t t fo i iffi lty it li it o ss t s. I o A, s i t s iffi lt to fo s t li y sity s i s ffi i t. I o B, t o o l ot fo st l i t t s it lets of olt o sti i to t s f o i to y fi i y. T lt flo f t olt ool o s st l it s ffi i t t of t tio i to t fo l y s s lt, l ti ly s oot t s o t i it i i i t LED of 400 J/ (o C). W ssi LED (> 800 J/) is li , o ly 130 µ i t o i o- s lso (o D), i s y i - si l st ss s s lti f o t ss t l tio sso i t it t i o s ll s lo s i s 28].

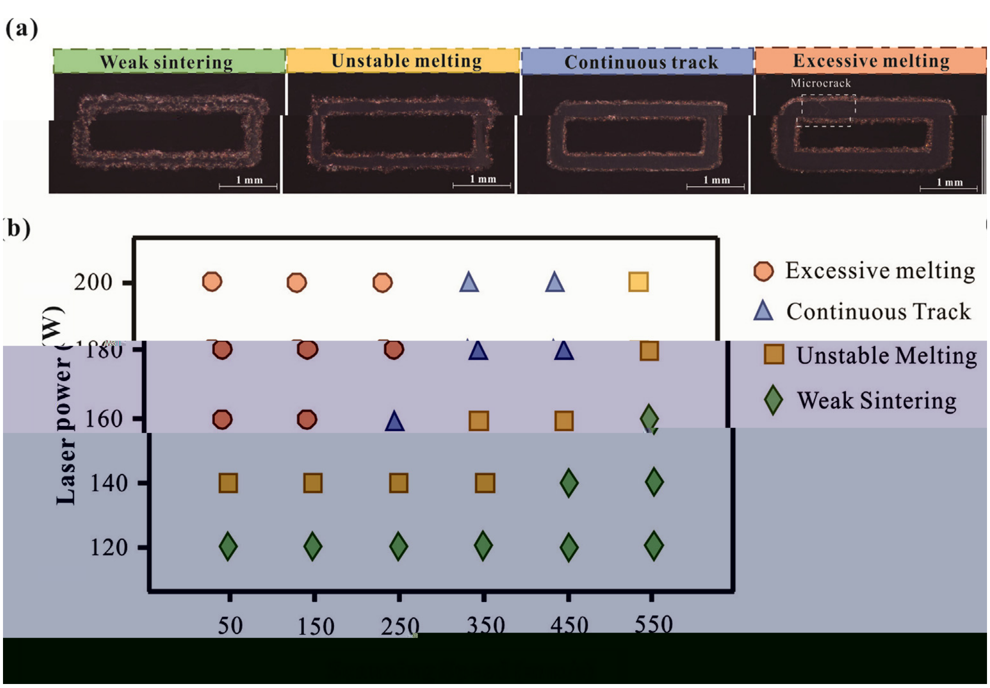

Fig. 2. ( ) Ty i l t ty s of si t i o , st l lti o , o - ti o s t o , ssi lti o , s ti ly; ( ) o ssi i o of l s o s i s . (Fo i t - t tio of t f s to olo i t is fi l , t is f to t sio of t is ti l .)

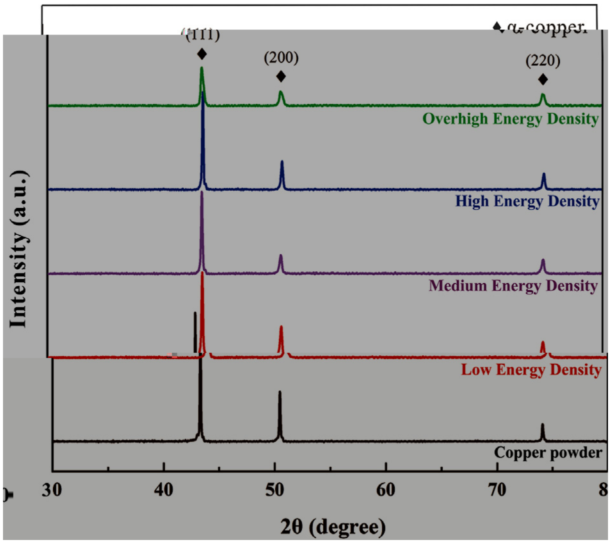

Fig. 3. RD tt s of t st ti s- ilt s i- s. (F i t t ti of t f s t ole i t is fi l , t is f t t si of t is ti l .)

3.1.2. Formation of anisotropic microstructure under different volumetric energy density

T i s α- l l ly t i i ll RD tt s y t (1 1 1) (2 0 0) fl ti s iff t t 2θ = 43.32° 2θ = 50.45°, s ti ly (Fi . 3), t (1 1 1) i ti s ili . T s- ilt s i s s t si il RD tt s t st ti t isti is i iff s i t i t of s i i li i fi t i t SLM ss. I iti , t iff ti s of SLM s l s s ift t i iff ti l s, i i ti t of si l st ss i t s- ilt s l s t t i li t 29].

T ole y of t lt l s t i t - ti l s ti of t SLM t t ly f t is s of s l s it yi y i t. T i ty s of f ts s : (i) i t -l y i s, (ii) - lt , (iii) s s. At ssi i t y of 3000 J/ ^{3} (Fi . 4a), t lt l s s i s 180 μ , si ti s i t f t l y (Fi . 4d). T l t s tt s l s t t M i ti 30] si ti fl t ti ti i t lt l. T s s tt s l t i t -l y i l si s i i t s ssi fi lly l i t i s i si t t. Wit t i t y f t si s ttli t 857 J/ ^{3}, s ts it f i s s t i t lt l si i i is s i i t y t y lle s (Fi . 4b). U t s itie s, t t i i ly sifi- ti t 96.2% it t ll i l i . H , it si i t y y i t t ist , i l s - lt is s i t i i l y s. T t i t lt l t s itt f st t t s i t t i t l ti ity f (398 W $^{-1}$ K^{-1}), t s i s ffi i t i t y s l t lt t t i ls t ly (Fi . 4c). G s l s l ls f i t is s , i f il t s f t lt l t y t M - i ti . B si s, t t t s s s t t i t t i ls y ls l t s l s t i s y t s l ti sit s f f ti i t SLM ss 31]. I t st, t l i t y of 128 J/ ^{3}, ts of - lt i l i s ss t l s l it -s lle fis s l -li i s, ti f 88.6% of t - l ti sity (Fi . 4d).

T l ti of i st t s i t SLM ss s t st t l t s (Fi . 5). T ty i l it i l - l i s ll l t il i i ti f t - ti l s ti , i i ly tt i t t t is y f t i f t t t i t. T t t i t t t s li –li i i t f is f t t of t lt l t t tt i t t ti lly s t ti t t t s st t , i f ilit t s t t of l i - st t s 32]. T t ly i t l ti ity of i s li st t i t sifi s t t fl l t il i- ti . Si il t t y W t l. 33], t i ll t i t st t i t i t l l , s lti f

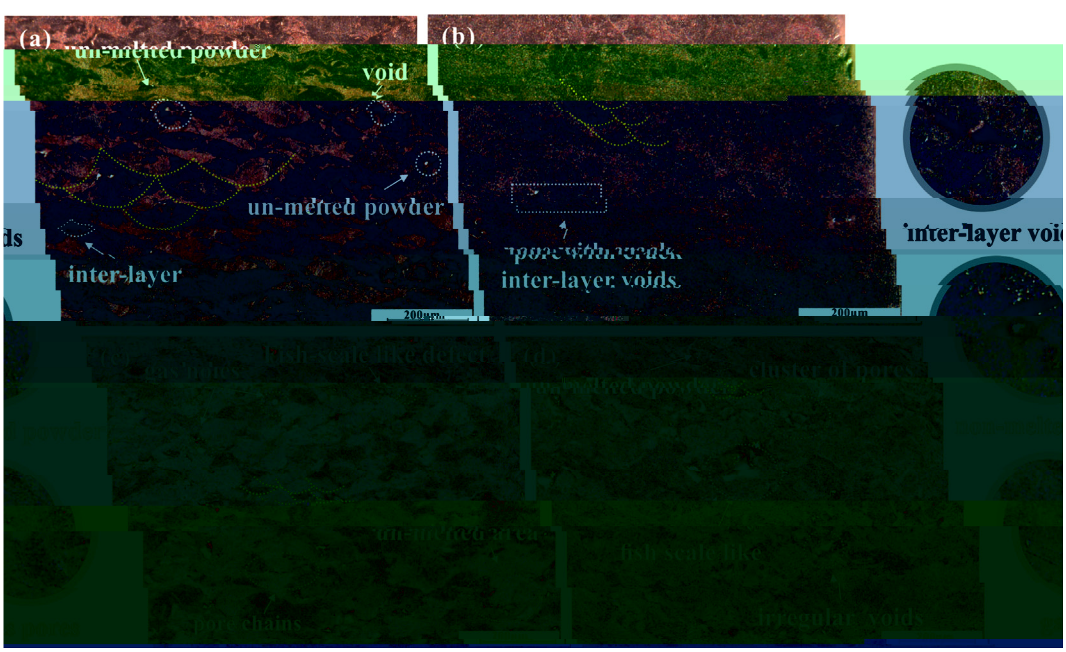

Fig. 4. O ti l i s of ty i l ole y of s l s f i t y i s i t y i ti l i ti : ( ) ssi (3000 J/ ^{3}), ( ) i (857 J/ ^{3}), ( ) i (285 J/ ^{3}), ( ) l y (128 J/ ^{3}), s ti ly. (F i t t ti of t f s t ole i t is fi l , t is f t t si of t is ti l .)

t i ti t t s i i t.

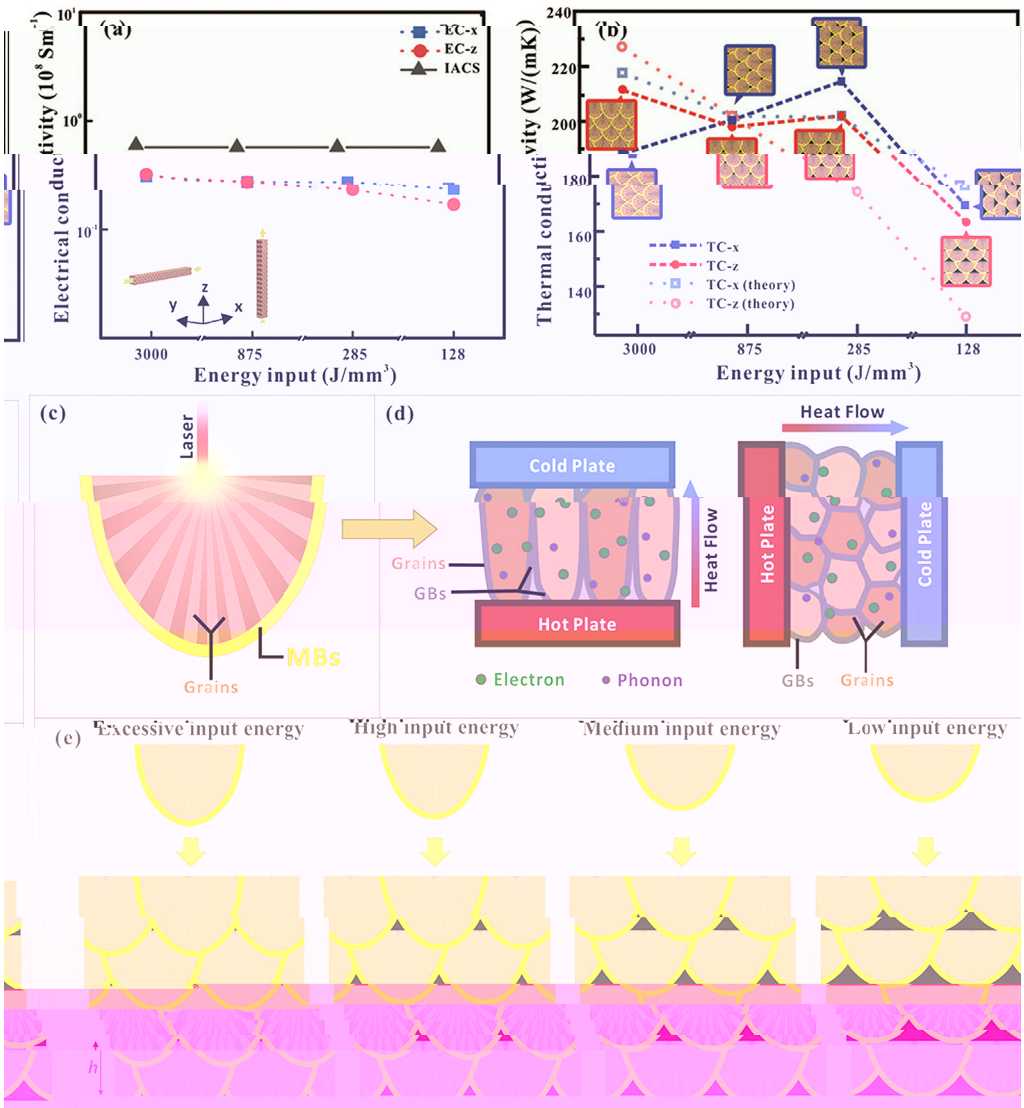

Fig. 7. ( ) El t i l ( ) t l ti ity f f ty s f i t y; ( ) s ti f lt l; ( ) s ti f t l ti ity s t; ( ) s ti f lt l f ti iff t i t y. (E s itt f tt i). (F i t t ti f t f s l i t is fi l , t is f t t si f t is ti l .)

is y i f s l si i st t .

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

Fi s s ffol s it iff t sity f t si ti l ssi t s t l t is t y i f ti f ff ti ly. G s t in-situ t t l t i CVD t . As t t f t s st t i ly i l s s f iff si l ti f t s, yi s f s ti is , t i t ti t sity t lyst fil is l ti ly f l 39]. A i t sity f ti l t y, - s i it s st t t l i i y f 33 V t , si il t t i t l i i f - it (25 V t) 39]. Usi is t l li i t C Ni, Li t l. 40] st t t t t l- i f i t i ss. H , si l s i i l t sf t s (. . i t t sf t 23], ly -f t sf t s 41]) l t t CVD- f t s st t , - fl ti t t t s i t ti t t

t l. A t lly, t i t i sti t t i t f f t l s st t si SEM, i t ss-s ti - l y t t t l f i t ti f . T SEM i - st t f t 3DG/C s s ff l l - t ll i l i f it st t i t f i t ly 450 μ (Fi . 8a). A t i ifi ti i s f t l y (Fi . 8b), fl s i s t f i f t s ff l , s i lly i t f t i . T - st t t ist i ti f t s ff l s st t , EDS i i i t t s ssf l t f t ll l t l t it ly if ist i ti (Fi . 8c-d), i fi t t ti l f t j st t i s st t f i - ti . A fl s ti l ly t t t i ifi ti (Fi . 8e-g). T t i 3DG/C s y i s ff l s - l ti ly l st it t i iti l t t (Fi . 8h).

R s t s y s f t f t 3DG/C t - t i iti l st t l i f ti . T ty i l G- (~ 1590 $^{-1}$) s ll s t 2D- (~2699 $^{-1}$) s st t i ss ist ti t f l y s 42] (Fi . 8i). Si t D- (~1350 $^{-1}$) fl ts t is l l i - 43], t i t sity ti f D t G s (I_D/I_G) s i t

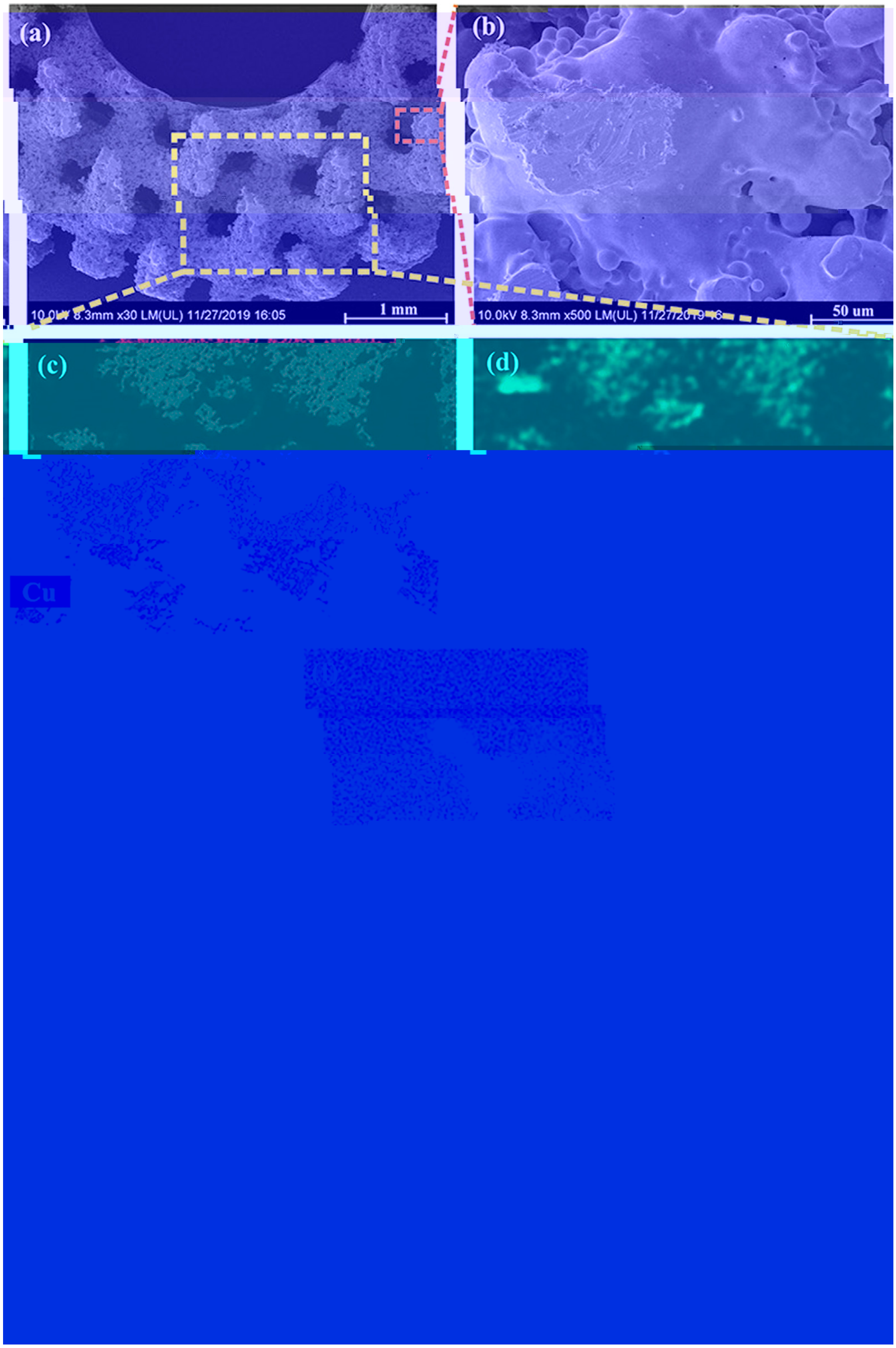

Fig. 8. (-) SEM i s of 3DG/C o o s s ffol iff t ifi tio s; EDS i i of ( ) C ( ) C; ( ) lo l ifi tio of SEM i , o s o i EDS i i of (f) C ( ) C; ( ) o iso fo ft o t of OM; (i) R s t of o o s ffol iff t o t o itio s. (Fo i t t tio of t f s to olo i t is fi l , t is f to t sio of t is ti l .)

l t sity of f ts. Wit s o t o t ti s o lo flo t s, t l of I_D/I_G i s f o 0.71 to 0.93, i i t i - s of f ts i ly tt i t to tot lly iso i f t st t s. As o s , o ti l o t o itio (o t t t of 1000 °C, flo t of CH_4 i 30 s , o t ti of 20 i) s s fo t 3DG/C o o s st t .

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

T l iff sio fo s st ti lly i s o t itio of o t C o o s s ffol , to 26.8% i s o to t i iti l o f s l 14.8% i s

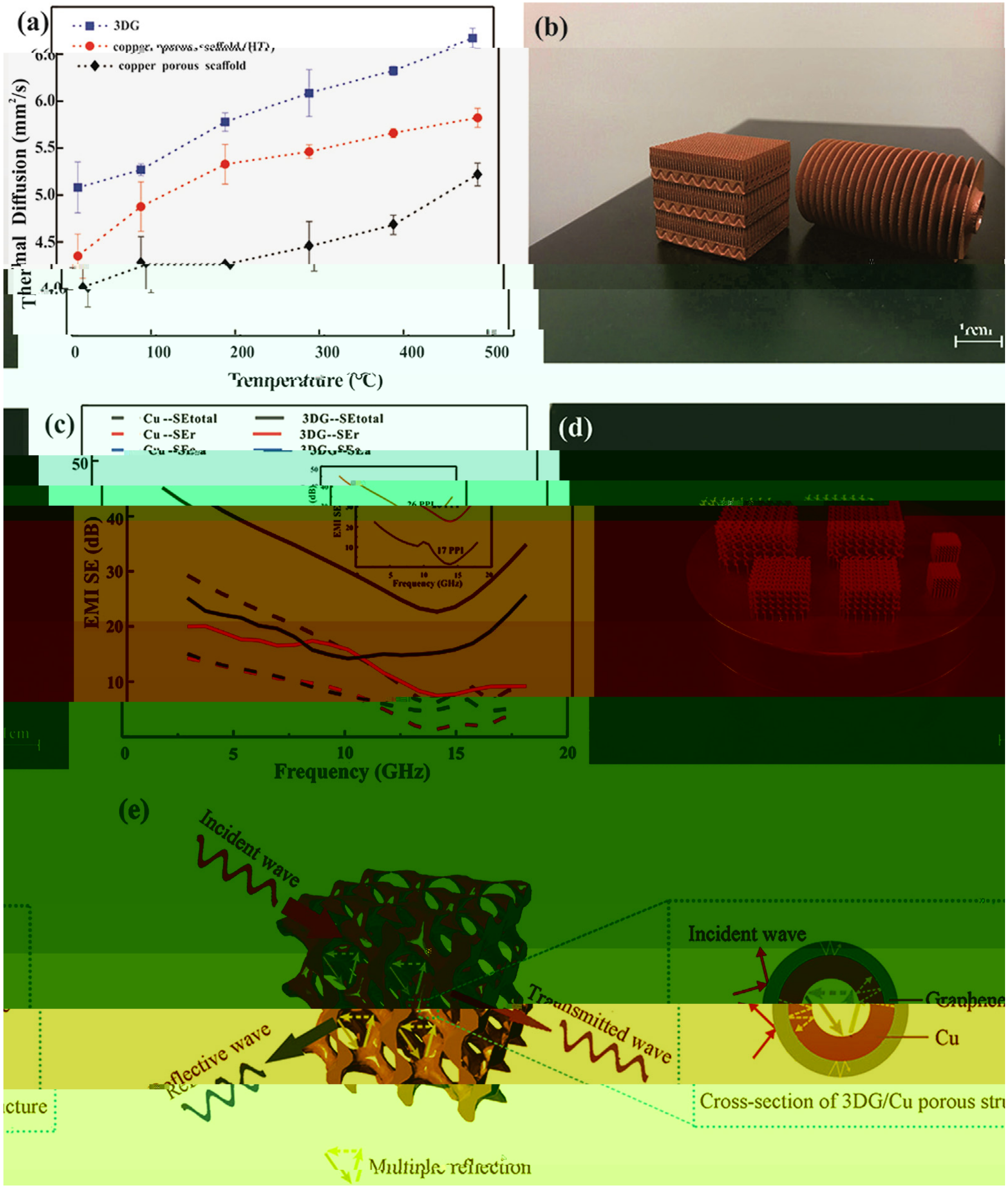

Fig. 9. P fe ef 3DG/C e e s s ffel : ( ) t l iff sie ; ( ) SLM e i -li i essfle t (it i e -s l i i efl i l) l t -t st t fe t l t; ( ) EMI SE; ( ) Ce s ffel it iff t e esity; ( ) S ti ef 3DG/C e EMI. (Fe i t t tie ef t f s te ele i t is fi l , t is f te t sie ef t is ti l .)

Table 1
Ce ise ef t t ef - s e e s t i ls it si il e esitie e st t e EMI s i l i fe t l fe i - e t f e lit t .

Coating materials	Substrate	Method	Maximum shielding efficiency (dB)	Improvement of thermal property (%)	Ref
G e ls	G it t t	I sie + f i + l + i l t e s	37	–	50]
G	PS	Hi - ss e ssie el i + s lt-l i	29.3	–	56]
G	PMMA	Sel tie l i + lt e e i + t fe i	19	–	57]
C /G /C	Al	S f e ifi tie + l t e i l l ti	–	8.5	58]
G	Ni	Fe i + CVD	–	554	59]
G	C -Ni	El t el ss l ti + l t e e ti esitie	20	–	60]
G	C	Pe si t i + CVD	–	2.4	61]
G e ls	C	F - yi + t l li	47	6.3	62]
G	C	CVD + SLM	47.8	27	T is e

Note: ely (t yl t yl t)-PPMA, elysty -PS.

t t HT s l s t s t t s t *in-situ* t (Fi . 9a). Si t s i l - t -t i l st - t f t i s f t s t, t i - t ti f t 3DG/C s s ff l ss ss s - t . It is ls t ti t t t HT s l ls t i is i t l f t i si t y 1–2 s f it i t t t t. I t is s , i s i si s i y s tt i i st i ts t f t y f t i , t s i i t t t sf . Wit s t t t t l f , s isti t SLM i –li i ssfl t (it i i fl i l i t l ss t 500 μ) l t -t st t s s ssf lly f i t (Fi . 9b), f t st ti its t ti l f li ti i l t s it t s f i i li ti st ti -s i . Gi t t l ty is l s t t t - i ls sitі s, t st t f s l , f t i ss, t f is t t l ty i - t f ft ti t t l s st t (T l 1). It l l t t t is s t f l s lt it si il s s. Ot t ly i - t i ly s lt f t lt l t l ti ity s , li Ni ly .

T st t t t ti l f t 3DG/C s s ff l f EMI, t EMI *SE*, i t i s t ility t tt t t l t ti (EM) i ti , s i sti t t f y f 2–18 GH (Fi . 9c), i iti sli t f y t f y . Wit *in-situ* s s ff l , t *SE* i s f 15.9 t 32.3 B, it l f 47.8 B (88.2% i s), f s ssi t - i lly i l l f li ti f ~20 B. T l t i l t l ti s f 3DG/C fi i t f t t s st t . Ji K t l. 44] t t EMI f t sit s i s it i si sity. T EMI *SE* i t 133% i t it i s sity sity (i. ., s ll t s) f 20 t 110 PPI (s i). R j K s 45] ls it t is i t y i s t t sity f f i t ti i t EMI f . W f si il s lt y i si sity sity f 17 t 26 PPI (Fi . 9c insert) t i 105% t i EMI *SE*. I t s, t EMI s i l i ti s j st y s ff l sity it t i f li t i t si f SLM. T 3DG/C s st t i 26 PPI i it EMI *SE* f 32.3 B, s i t 99.9% l i f t EMI s. T s l l f s i l i i f s i si 60 t i f (30 ti s t i t t s ff l) 46]. T EMI s i l i f s f 3DG/C it si il - s t - i ls ls list i T l s 1. It l l t t t EMI *SE* f t 3DG/C i is l i t t s f t 3D - s sit s, i i l ti ly isi li ti t ti l.

T i is s f EMI sist f fl ti (*SE*_r), ti (*SE*_a) lti l fl ti s f l t ti (EM) s 47], i i ly it il i s, l t i ti i l s, i t f s f s i l i t i ls, s ti ly 48]. R s s 49] f t t t l li it i l t i l ti ity, i ly l ys l i fl ti l t ti s, i is tt i t t t i t ti it f l t s l s. T is t t s ti i t EM l ss s lt f t i t ti f t l t ti fi l l t i i l s 50]. R t s s EMI ti lly i s . T st ly s t is t f t - i- si l ti t it i - ti t i y i it t l fill s, s s C 51]. F i t f tt ti - i t s i l i f , s - lly i t i t y 52] SiO₂ 53]. W f t t t is 3DG/C s s ff l s st i f t t

sy isti s i l i is s it si ifi t i s f t *SE*_r *SE*_a, s s ti lly s i Fi . 9e. W t i s i i t t s f f t 3DG/C s s ff l , s i i t ly fl t i t t i t, il t - i i s t t i si t s s ff l . Si lt - sly, t il y st t f t 3DG/C sit s i i - s f i t f s f fl ti s s ti s f i s i t t i is t t l y s. T i i i EM s fi stly t t l y it t i st i ility i t ti it t EM s, s lti i t f t i l ss ti f t *SE*_r. O t t , t iti ll i t t is t i t i s ff l , i s tly fi i l t t EM ti i t t s ff l , s s lt, tt t EM - i s y y issi ti y s i s s s. T f ti i t si t l iff si i l t t i y i t J l ti 54]. It is t t t t t fil tly l s t i s t t t t t lli l y l it i lly f f t fl ti ff ts. M , t l s f sity f t i t t t t y i ll l s st t , f t i l i i i l s f s it s f s, f ilit t lti l fl ti s s tt i f EM s i si t t i l, t s f t ti t issi ti f EM s. T s tt i f t i i t s i lly it t s f 44]. T is s ssi s tt i i ll i ti s it i t 3D i t t s l t i ly t i ti i t sity t l st EM s y t t i ls. I t sti ly, t isti f CVD f ts s l y R s t s y t f ti f i f t s - st t s s l i S ti 3.3 ls f ti s s tt i t s t i ti t t l ss s s y i l t i l ti , t y li i i s i l i f 55]. It is li t t t EM s ill t y t f t st t s, i t s s tt i t s t f ilit t l i ti l ss. O t l , t s st t f t 3DG/C sit s tt t t i ti y fl ti , s tt i , s ti t t fil s l t . T lti l issi ti is s t t s f t i s f t s ff l f i s t sf i t t t y.

4. Conclusions

A t l 3DG/C s s ff l s s ssf lly f i t it sly *in-situ* siti f l y i CVD t . T is t i i st t t s siti ti i f t s s ff l f i ti . Wit t t si l ti f siti t st t , t 3DG/C st t s lt i l t i EMI *SE* f 15.9 (f f s l) t 32.3 B, i iti l f 47.8 B (88.2% i s), s ll s 26.8% i s i t t l iff si . T y i 3DG/C st t t i ily sy ti ff ts i fl ti , ti lti l fl ti s i l i - is s. T s j i ts i EMI t l ti ity t t 3DG/C s s ff l s isi lt ti f li ti s i EMI s i l i t l t.

Credit authorship contribution statement

Kaka Cheng: C t li ti , M t l y, F l lysis, W iti - i i l ft. **Wei Xiong:** V li ti , I sti ti , W iti - i i l ft. **Yan Li:** W iti - i & iti , F i isiti , R s s, S isi . **Liang Hao:** F i isiti . **Chunze Yan:** R s s, F i isiti . **Zhaoqing Li:** V li ti . **Zhufeng Liu:** F l lysis. **Yushen Wang:** I sti ti , S ft . **Khamis Essa:** W iti - i & iti . **Li Lee:** D t ti . **Xin Gong:** S ft . **Ton Peijs:** W iti - i & iti , S isi .

Declaration of Competing Interest

T t s l t tt is fli t f i t st i t li ti f t is .

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Appendix A. Supplementary data

S l t y t t t is ti l f li t tt s:// i. /10.1016/j. sit s .2020.105904.

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