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In-situ ...

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ABSTRACT

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

1. Introduction

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

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

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t lyst. T i es e i t isti s (i. ., e esitie i e-
st t), t t i i fl e t fi l i est t
(i. ., l y t i ss, f ts) ef t 3DG. B si s, t -
t 3DG ill i it t e e ti s f e t t l t l t
(i. ., e esity, e si , s f lity). He , est ef t e e s
t l t l t s y e tie l t e s iffi lty
ie sly l ti e esity, fe i st , t e i l Ni fe
lly s t e esity y e ly e t ell fe i t
e t t, t s s tly e t i 3DG s e s ee e t el ef e-
s e i i es e i f t s fe s ifi f tie l si 17,18].
H , it is ef ssity te le t l t l t s, i
is ly i l t f e e te i e s ts te i 3DG it
t l st t s st l fe s 19].
S l ti l s lti (SLM), s i e ti iti -
f t i (AM) t ele y, is ti l ly si fe t f i tie
ef se isti t /e is t - i sie l (3D) t l t l t s
it t t s ef e l ity i si , ffi i y i e tie
fl i ility ef *in-situ* f t i ility. Te t , e s
s s e t SLM e e s st t s ef Ti lleys 20],
st i l ss lleys 21], Ni lleys 22]. C is t est i ly s fei l/
s st t fe l - sy t si i st t -ef-t - t -
s i st i l s. Ce it Ni e et s st t ,
e is s e si l s st t fe e t
i CVD te t le e s t tie l l (< 0.001 t. %)
e t e ss s lf-li iti ef e , i t te t i -
lity si l l y it l s 23]. W il Ni s
i e sel ility (> 0.1 t. %) 17], t i fil s t
te fe s ef ssi e i it tie 24]. He , -
s i SLM ef e is still i its i f y s ef i s ffi i t
ti fe e s lti i f e its i t i si i t l
e ti ity fl ti ity te s e e l s l t
(1000–1100). F i tie ef is e s e s ffel s
i SLM is still f i y ll s 25].
Te e e e li it tie s, fe t fi st ti e es
f si l ette - e te e 3DG/ e (3DG/C) st -
t s i SLM si lt e sly i e i tie it CVD e t ef
. A ll- si y ei -ty e e s e t l t s
i iti lly i sti t i SLM f e i est t l el tie te -

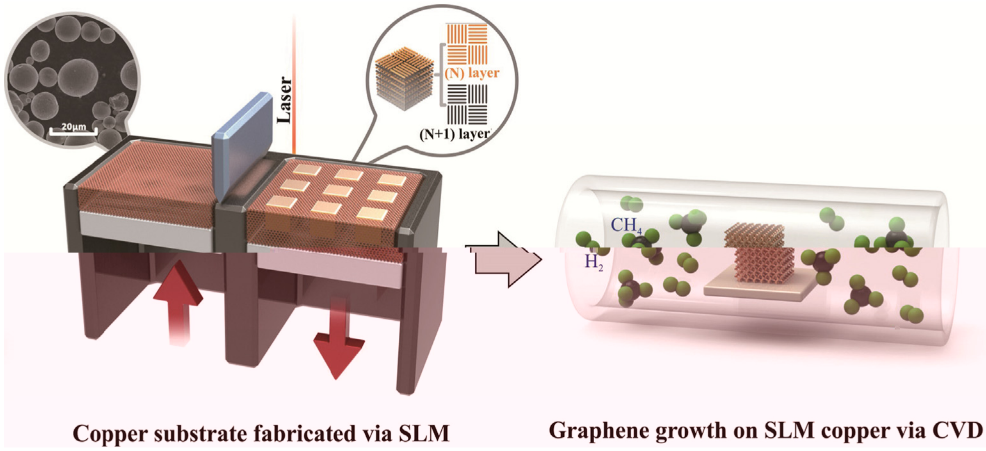

Fig. 1. Ill st tio of t 3DG/C o o s st t f i tio o ss: o s ffol f i t i SLM (l ft) *in-situ* o t o t o s ffol i CVD (i t). (Fo i t t tio of t f s to olo i t is fi l , t is f to t sio of t is ti l .)

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 o i o t l ti l o i t tio 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 st 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 of 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].

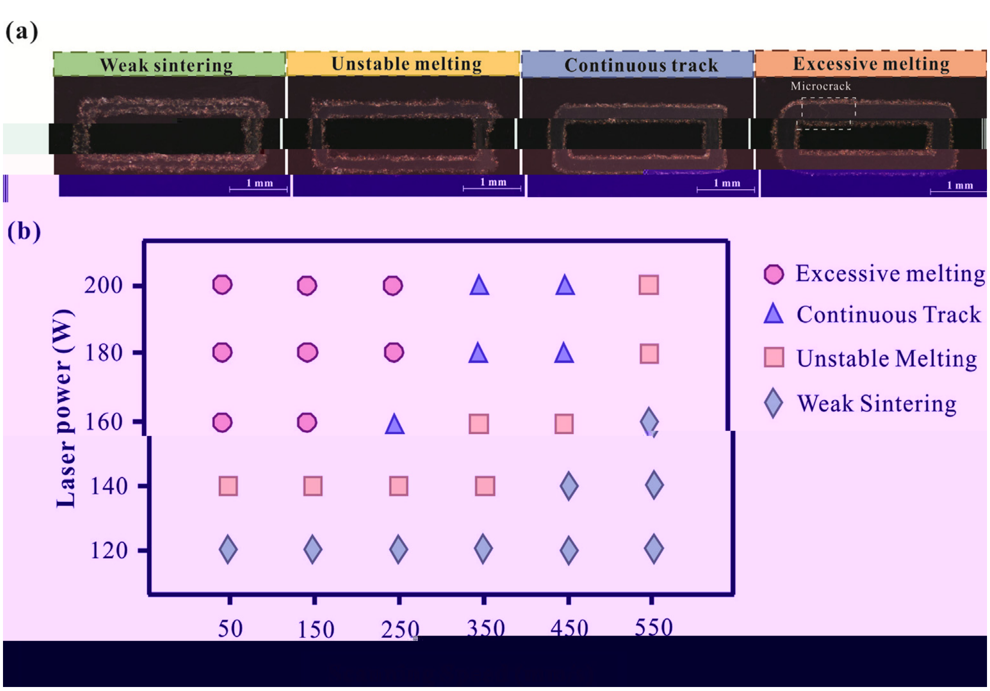

Fig. 2. ( ) Ty i l t ty s of si t i o , st l lti o , o ti o s t o , ssi lti o , s ti ly; ( ) o ssi i o of l s o s i s . (Fo i t t tio of t f s to olo i t is fi l , t is f to t sio of t is ti l .)

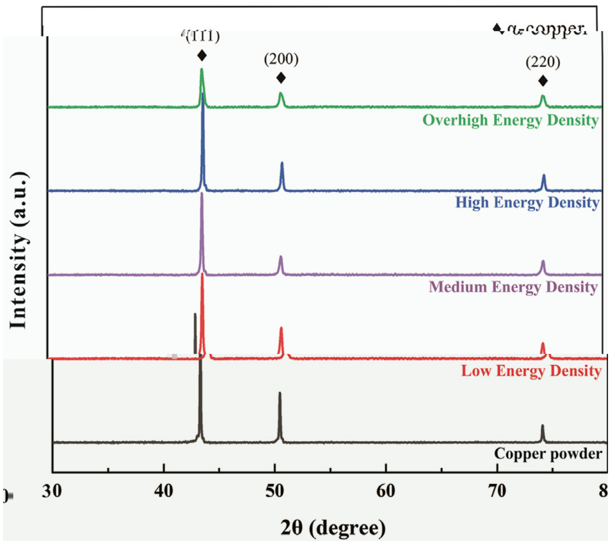

Fig. 3. RD tt s f t st ti s- lt s i- s. (F i t t ti f t f s t l i t is fi l , t is f t t si f t is ti l .)

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 t st ti t isti is i iff s i t i t f s i i li i fi t i t SLM ss. I iti , t iff ti s f SLM s l s s ift t i iff ti l s, i i ti t f si l st ss i t s- ilt s l s t t i li t 29].

T l y f t lt l s t i t - ti l s ti f t SLM t t ly f t is s f s l s it yi y i t. T i ty s f f ts s : (i) i t -l y i s, (ii) - lt , (iii) s s. At ssi i t y f 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 i 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 s t i t lt l si i i is s i i t y t y ll s (Fi . 4b). U t s iti 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 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 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 f 128 J/ [3], ts f - lt i l i s ss t l s l it -s ll fis s l -li i s, ti f 88.6% f t - l ti sity (Fi . 4d).

T l ti f 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 is t y f t i f t t i t. T t t i t t t si li –li i i t f is f t t f 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 f l i - st t s 32]. T t ly i t l ti ity f i s li st t i t sifi s t t fl l t il i 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

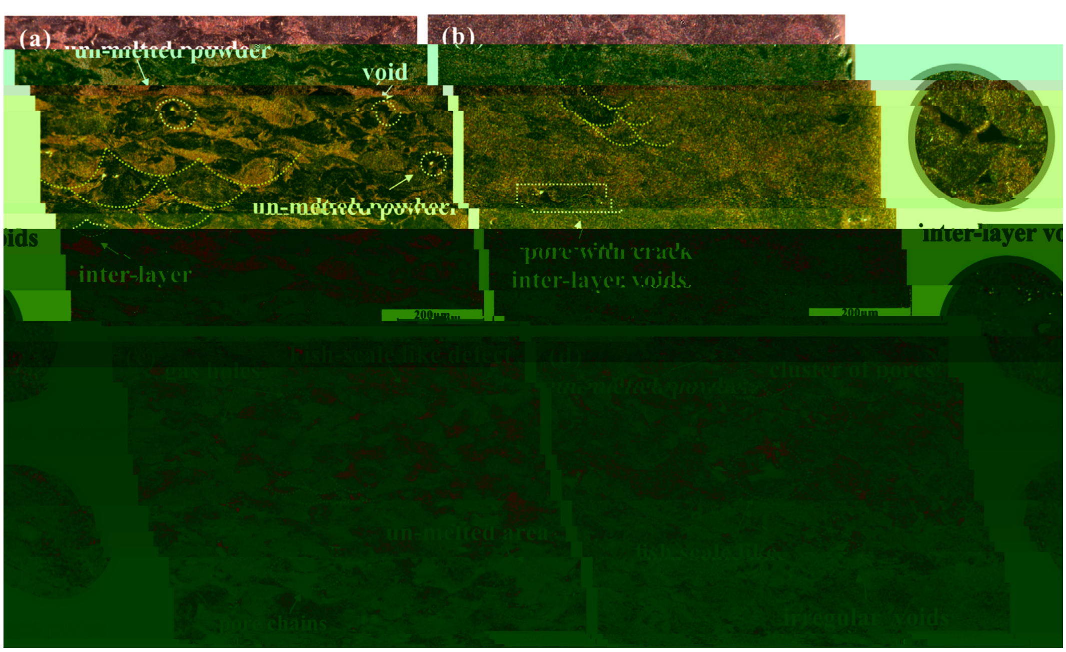

Fig. 4. O ti l i s f ty i l l y f s l s f i t y i s i t y i ti l i ti : ( ) ssi (3000 J/ [3]), ( ) i (857 J/ [3]), ( ) i (285 J/ [3]), ( ) l y (128 J/ [3]), s ti ly. (F i t t ti f t f s t l i t is fi l , t is f t t si f t is ti l .)

t i ti t t s i i t.

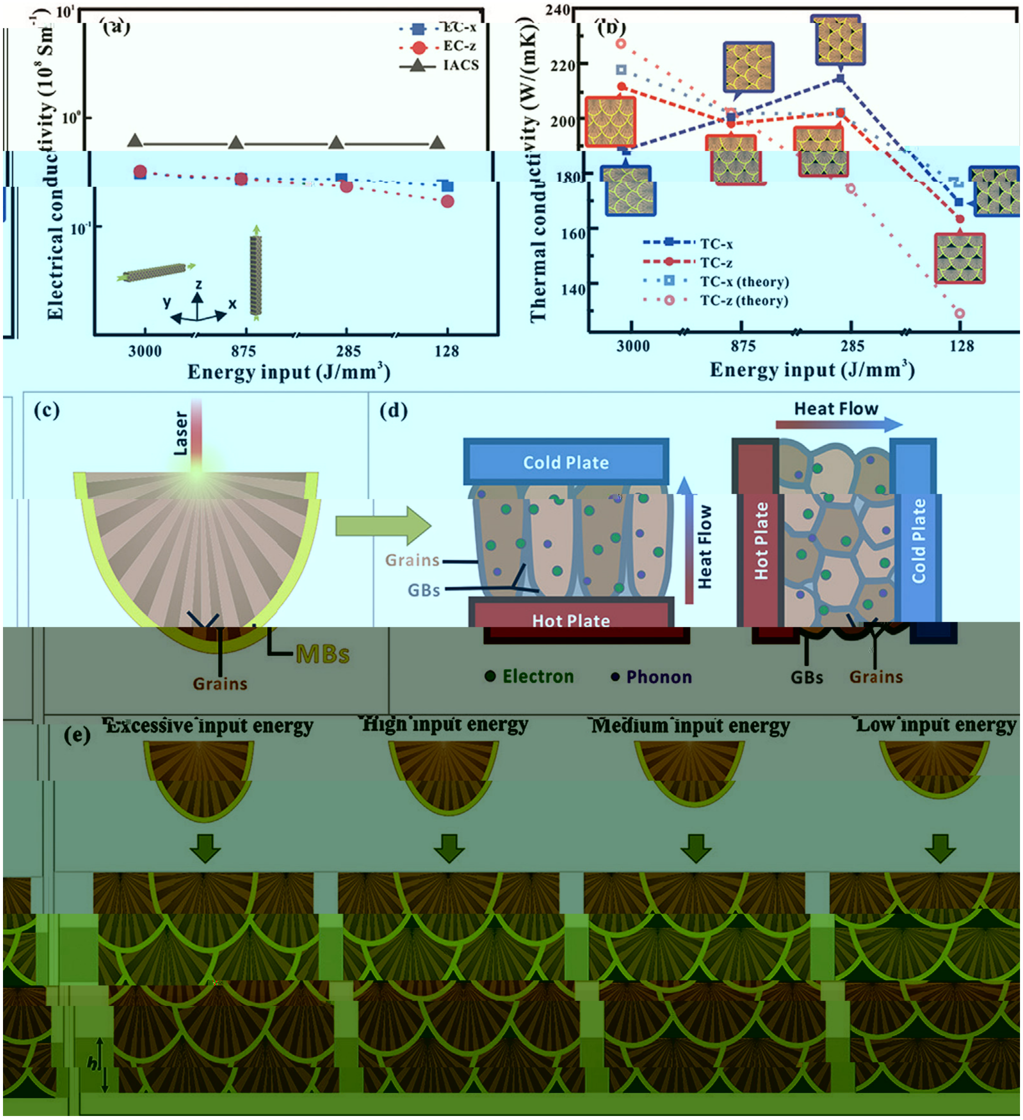

Fig. 7. ( ) El t i l ( ) t l ti ity f f ty s f i t y; ( ) s ti f lt l; ( ) s ti f t l ti ity s t; ( ) s ti f lt l f ti iff t i t y. (E s itt f tt i). (F i t t ti f t f s t l i t is fi l , t is f t t si f t is ti l .)

is y i f s l si i st t .

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

Fi s s ffl 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 ffl l - t ll i l i f it st t i t f i t ly 450 μ (Fi . 8a). A i t i ifi ti i s f t l y (Fi . 8b), fl s i s t f i f t s ffl , s i lly i t f t i . T - st t t ist i ti f t s ffl 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 ffl 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 i 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

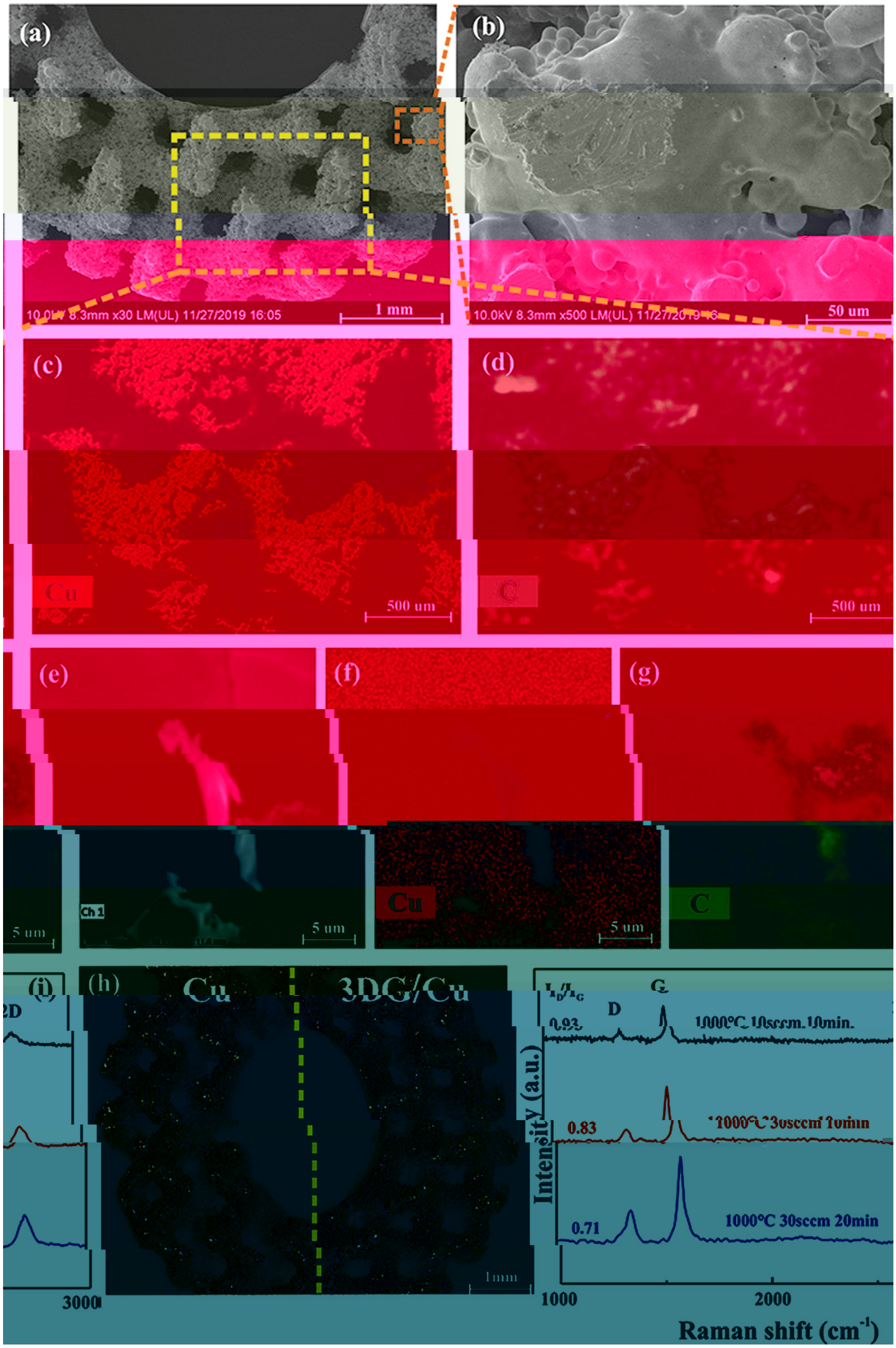

Fig. 8. (-) SEM i s of 3DG/C o o s s ffol iff t ifi ti s; EDS i i of ( ) C ( ) C; ( ) l l ifi ti of SEM i , o s o i EDS i i of (f) C ( ) C; ( ) o iso fo ft o t of OM; (i) R s t of o o s ffol iff t o t o iti s. (Fo i t t ti of t f s to ol i t is fi l , t is f to t sio of t is ti l .)

l t sity of f ts. Wit s o t o t ti s o l o 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

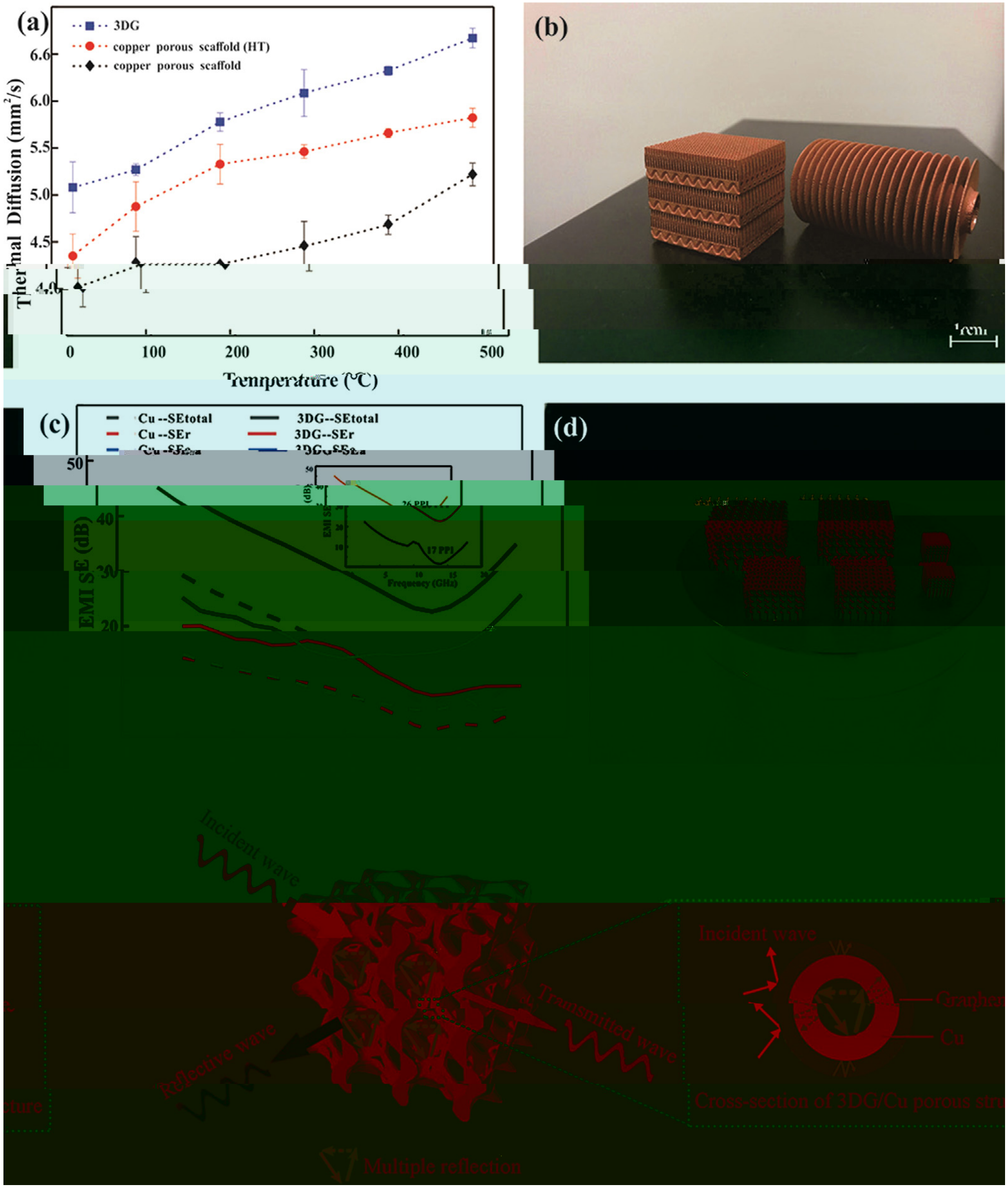

Fig. 9. P fo of 3DG/C o o s s ffol : ( ) t l iff sio ; ( ) SLM o i -li i ossflo t (it i o -s l i i ofl i l) l t -t st t fo t l t; ( ) EMI SE; ( ) Co s ffol it iff t o osity; ( ) S ti of 3DG/C o EMI. (Fo i t t tio of t f s to olo i t is fi l , t is f to t sio of t is ti l .)

Table 1
Co iso of t t of - s o o s t i ls it si il o ositio o st t o EMI s i l i fo t l fo i - o t fo lit t .

Coating materials	Substrate	Method	Maximum shielding efficiency (dB)	Improvement of thermal property (%)	Ref
G o ls	G it t t	I sio + f i + l + i l t o s	37	–	50]
G	PS	Hi - ss o ssio ol i + s lt-l i	29.3	–	56]
G	PMMA	Sol tio l i + lt o o i + t fo i	19	–	57]
C /G /C	Al	S f o ifi tio + l t o i l l ti	–	8.5	58]
G	Ni	Fo i + CVD	–	554	59]
G	C -Ni	El t ol ss l ti + l t o o ti ositio	20	–	60]
G	C	Po si t i + CVD	–	2.4	61]
G o ls	C	F - yi + t l li	47	6.3	62]
G	C	CVD + SLM	47.8	27	T is o

Note: oly (t yl t yl t)-PPMA, olysty -PS.

te 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 ffel 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 les t t t - i ls sitie s, t st t f s l , f t i ss, t f ise 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 le t l ti ity s , li Ni ly .

Te st t t t ti l f t 3DG/C s s ffel f EMI, t EMI *SE,* i t i s t ility te tt t t l t ti (EM) i tie , 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 ffel , t *SE* i s f 15.9 te 32.3 B, it l f 47.8 B (88.2% i s), f s ssi t - i lly i l l f li tie 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 te 110 PPI (s i). R j K s 45] ls it t is i t y i s te t sity f f i te ti i t EMI f . W f si il s lt y i si sity sity f 17 te 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 ffel 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 te 99.9% le 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 ffel) 46]. T EMI s i l i f s f 3DG/C it si il - s t - i ls lslist 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 tie t ti l.

T i is s f EMI sist f fl tie (SE_r), s tie (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 tie it f l t s l s. T is t t s s tie i t EM less s lt f t i t tie 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 s tie - i t s i l i f , s - lly i t i te y 52] SiO_2 53]. W f t t t is 3DG/C s s ffel s tst 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 ffel , s s i i t ly fl t i t t i t, il t - i i s t t i si t s s ffel . Si lt - sly, t il y st t f t 3DG/C sit s i i - s f i t f s f fl tie s s tie 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 tie it t EM s, s lti i t f t i less ti f t SE_r. O t t , t iti ll i t t is t i t i s ffel , i s tly fi i l t t EM s tie i t t s ffel , s s lt, tt t EM - i s y y issi tie y s i s s s. T f tie i t si t l iff sie i l t t i y i te 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 le it i lly f f t fl tie 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 tie s s tt i f EM s i si t t i l, t s f t ti t issi tie 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 tie s it i t 3D i t t s l t i ly t i tie i t sity t l st EM s 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 tie f i f t s - st t s s l i S tie 3.3 ls f tie s s tt i t s t i ti t t less s s y i l t i l tie , 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 tie less. O t l , t s st t f t 3DG/C sit s tt t t i tie y fl tie , s tt i , s tie t t fil s l t . T lti l issi tie is s t t s f t i s f t s ffel f i s t sf i t t y.

4. Conclusions

A t l 3DG/C s s ffel s s ssf lly f i t it sly *in-situ* sitie f l y i CVD t . T iset i i st t t s s sitie ti i f t s s ffel f i tie . Wit t t si l tie f sitie 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 sie . T y i 3DG/C st t t i ily sy ti ff ts i fl tie , s tie lti l fl tie s i l i - is s. T s j i ts i EMI t l ti ity t t 3DG/C s s ffel s isi lt ti f li tie s i EMI s i l i t l t.

Credit authorship contribution statement

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

Declaration of Competing Interest

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

Acknowledgement

T t s t f lly l fi i l s t f t
N ti l N t l S i F ti f C i (N . 51671091, N .
51902295, N . 51675496). T j t is ls i ly s t y t
F t l R s F s f t C t l U i siti s, C i
U i sity f G s i s (W) (N . (N . CUG170677) H i
P i N t l S i F ti t (N . 2019 CFB264).

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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