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polymer fibre membranes by electrospinning technology and its application to lightemitting diodes

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Abstract

Recently, organometallic halide perovskites have shown attractive application prospects in photoelectric devices depending on their excellent electro-optic properties. However, their poor stability has greatly limited their practical applications. Here, methylammonium lead tribromide (MAPbBr₃) crystals are protected by polystyrene (PS) fibre membranes using electrospinning technology. The MAPbBr₃@PS composite fibre membranes fabricated in this work not only show strong photoluminescence properties but also excellent stability: 70% of the fluorescence intensity of MAPbBr₃@PS is maintained after soaking in water for 30 days, 85% after leaving at 95 °C for 350 min, and 90% after irradiating under UV light for 100 h. The excellent stability of the MAPbBr₃@PS fibre membranes may be attributed to the hydrogen bonds between the MAPbBr₃ crystal and the PS fibre. In addition, a high-brightness white-light-emitting diode based on MAPbBr₃@PS fibre was fabricated, which fully demonstrates its application prospects in the field of colour conversion. © 2020 Society of Industrial Chemistry

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Keywords: polystyrene; membranes; perovskite; electrospinning

INTRODUCTION

In recent years, organometallic halide perovskites (OMHPs) have attracted more attention and are used in a variety of optoelectronic devices, such as solar cells,^{1,2} photodetectors^{3,4} and light-emitting diodes (LEDs), due to their attractive electrical and optical properties.^{5,6} However, the hypersensitivity of perovskite to the external environment considerable limits their wide application. It is important to investigate simple and effective ways to improve the stability of OMHPs.^{7–10}

As a traditional polymer engineering material, polystyrene (PS) is widely used in architecture, transportation and daily life because of its low cost, excellent mechanical performance, simple manufacturing process and high yields.^{11–14} Its homopolymer is an amorphous brittle material, which has good hardness and strength, excellent transparency, is easy to process and can be made into a variety of products.^{15,16} It has a wide range of applications in the fields of construction, packaging materials, coatings and home appliances. In addition, PS can be recycled and reused to avoid environmental pollution.

In this work, trace perovskite crystals are mixed in PS film by electrospinning technology. The MAPbBr₃@PS composite fibre membranes fabricated in this work (where MAPbBr₃ is methylammonium lead tribromide) not only have strong photoluminescence (PL) properties but also show excellent stability: 70% of

the fluorescence intensity of MAPbBr₃@PS is maintained after soaking in water for 30 days, 85% after leaving at 95 °C for 350 min, and 90% after irradiating under UV light for 100 h. The excellent stability of the MAPbBr₃@PS fibre membranes may be attributed to the hydrogen bonds between the MAPbBr₃ crystal and the PS fibre. In addition, a high-brightness white LED based on MAPbBr₃@PS fibre was fabricated, which fully demonstrates the application prospects in the field of colour conversion and provides a new direction for the application of PS in the field of optoelectronics.

Electrospinning technology has proven to be a simple, high throughput and inexpensive method for preparing high crystallinity polymer fibre films. However, electrospinning techniques are rarely used to package MAPbX₃ (X \equiv I, Br and Cl) with various polymers. Tsai *et al.* mixed polyaniline and perovskite by

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electrospinning.¹⁷ However, due to the defects of the polyaniline itself, its water stability was not significantly improved. Liao *et al.* used electrospinning to mix CsPbBr₃ with PS,¹⁸ but technical problems did not improve the thermal stability of the perovskite. Therefore, it will be meaningful to construct a PS fluorescent fibre film with high stability.

Here, a photoluminescent functional PS fibre film was successfully constructed by doping a small amount of perovskite during the electrospinning process. Further, the water resistance, heat resistance and oxygen resistance of the MAPbBr3@PS fibre films were systematically studied. By changing the composition and type of metal halides and non-metal halides, the MAPbBr3@PS fibre membrane can cover the entire PL emission range. With commercial blue LED lamps as the light source, white LEDs have been successfully constructed using the MAPbBr3@PS film. It not only provides a method to improve the stability of perovskite but further expands the application of optically functional PS fibres in the field of optics.

EXPERIMENTAL

Materials

N,*N*-Dimethylformamide (DMF), methylamine (CH₃NH₂) (40 wt% in water) and hydrobromic acid (HBr) (48 wt% in water) were purchased from Sigma-Aldrich (Shanghai, China). PS ($M_w \approx 200\ 000$) and silicone resin were obtained from Aladdin (Shanghai, China). All reagents were used as received without further treatment.

Synthesis of ammonium methyl bromide CH₃NH₃Br (MABr)

MABr was prepared according to the previously reported method by mixing CH₃NH₂ and HBr in a ratio of 1.8:1 (v:v). Typically, 9 mL of HBr (48 wt% in water) was added dropwise to 18 mL of CH₃NH₂ (40% in ethanol) slowly in a 100 mL round bottom flask in an ice bath with constant stirring for 4 h. Then, the mixture was purified by reduced pressure distillation (*ca* 50 Torr) with a rotary evaporator equipped with a water bath at 60 °C for 4 h. The crude product was washed with absolute ethanol three times and then recrystallized from anhydrous diethyl ether. The white powder of MABr crystal can be collected after drying overnight in a vacuum oven at 60 °C (Fig. S11 is the XRD of MABr powder).

Preparation of MAPbBr₃@PS fibre membrane

MAPbBr₃@PS fibre membranes were fabricated by the electrospinning process at 25 °C and 20% humidity. A uniform transparent solution can be achieved by dissolving 0.076 g of PbBr₂, 0.023 g of MABr and 1.25 g of PS in 5 g of DMF under stirring. Then, the above precursor solution was stocked in a syringe with a stainless-steel needle of 0.25 mm, with a fixed potential of 16 kV applied across a typical collection distance of 24 cm (Fig. 1).

Fabrication of LED devices

First, $(Sr,Ca)AlSiN_3:Eu^{2+}$ phosphor was mixed with resin glue uniformly as the red emissive layer; then it was coated evenly on the PS/CH₃NH₃PbBr₃ film. The white LED device was obtained by bonding the film sample mentioned above onto the blue LED chip. A thickness of 200 µm of PS/CH₃NH₃PbBr₃ film was used in this process.

Characterization

The structure, morphology and composition of OMHP@polymer fibres were characterized by XRD (Smartlab, Rikagu, Japan),



Figure 1. (a) Water contact angle of PS at different concentrations. (b) Processing scheme for $CH_3NH_3PbX_3@PS$ fibre film using one-step electrospinning methods.

ultra-high-resolution thermal field emission SEM (JSM-7600FPlus, JEOL, Japan) and TEM (JEM-2100F, JEOL) equipped with an energy dispersive spectrometer. The PL, photoluminescence quantum yield (PLQY) and fluorescence lifetime were measured with a fluorescence spectrometer (Fluromax-4, Horiba, USA) equipped with quantum yield attachments, temperature control attachments and fluorescence lifetime attachments. UV-visible measurements were performed on a UV-visible-near-IR scanning spectrophotometer (Cary 5000, Agilent, USA) equipped with an integral sphere. IR tests were performed on a Fourier transform IR spectrometer (IS50, ThermoFisher, USA). A video optical contact angle measuring instrument (SPCA-X-1, Harke, China) was used to measure the contact angle. The LED was tested at room temperature by using a light distribution testing system (C9920-11, Hamamatsu, Japan). The UV stability test was done using a UV lamp, power frequency 50 Hz (China).

RESULTS AND DISCUSSION

First, 14%, 16%, 18%, 20% and 24% PS solutions were used to prepare fibre films by the electrospinning process; the water contact angles of the solutions are shown in Fig. 1(a). For large area membranes, the contact angle data were obtained by testing five to eight points at different positions in the film, and the average value of the data was obtained. It was found that when the concentration was 20% the contact angle of the PS film was 152°, which provides good water stability. Further, MAPbBr₃@PS fibres were also fabricated by the one-step electrospinning technique, the schematic of which is shown in Fig. 1(b) (see the Experimental section for details). It is well known that PS fibres have outstanding hydrophobic properties, which can be confirmed by the contact angles of the PS films (Fig. S1). It can be seen that the water contact angle of the PS fibre prepared by electrospinning is obviously larger than the water contact angle by spin coating, which laid the foundation for its stability. Due to the electrospinning

effect and swellability of PS in DMF, MAPbBr₃ nanocrystals can be distributed in PS fibres uniformly in size and space.

Figure S2 shows the SEM images of MAPbBr₃@PS fibre with different concentrations of MAPbBr₃ from 1.25% to 25% in solution. A different nanofibre film morphology can be achieved by changing the concentration of MAPbBr₃. The MAPbBr₃ crystals can evenly distribute in the PS nanofibres without any beading when their concentration is 10%. There are fewer surface defects of MAPbBr₃@PS (10% MAPbBr₃) nanofibres in the composite film, the uniform diameter of which is about 500 nm. The relative PLQY result also proves that 10% concentration of MAPbBr₃ is optimal (Fig. S3). More importantly, the hydrophobicity of the PS fibres is obviously increased due to their pleated surfaces, so the perovskite nanocrystals can be protected in the specific structure (Figs 2(a)-2(c)). It can be clearly seen from the TEM image (Fig. 2 (d)) that all of the MAPbBr₃ crystals are well dispersed both on the surface and inside the PS fibres. It can be proved that the size and spatial distribution of the perovskite crystals can be effectively limited by electrospinning. In addition, the rod-shaped MAPbBr₃ crystals with a diameter from 10 to 20 nm, as shown in Fig. 2(d), can be attributed to the strong tensile force during the electrospinning process.⁹ Combined with energy dispersive spectroscopy, it is further demonstrated that MAPbBr₃ crystals are uniformly distributed inside the PS fibres (Fig. S4). The diffraction peaks of PS and MAPbBr₃ can be clearly seen from the XRD curves of the MAPbBr₃@PS fibres, as shown in Fig. S5, wherein the main peak responses detected at 16.3°, 18.43° and 21.7° are attributed to the diffraction of PS (PDF Card: 00-013-0836). The main peak responses detected at 15.17°, 21.3°, 30.63° and 34.25° are attributed to the diffraction of the (101), (121), (202) and (222) planes in MAPbBr₃ (PDF Card: 01-076-2758). It is thus determined that MAPbBr₃ crystals have been formed in the PS fibres. A large area of MAPbBr₃@PS fibre membrane (30×20 cm) can be achieved by the electrospinning process (Fig. S6).

As shown in Fig. S7, the UV absorption peak, PL emission peak and Tauc plot of MAPbBr₃@PS are at 515, 527 nm and 2.3 (band-gap) respectively.^{19–21} The PLQY of MAPbBr₃@PS fibres is detected by a fluorescence spectrometer equipped with an integrating sphere. It was found that the PLQY was distributed between 10% and 15.4% by testing the same batch of samples several times.

The PL lifetime is often considered as a sign of the quality of perovskite film, and the longer life the better performance it will have.^{18,22} The time-resolved PL spectrum of MAPbBr₃@PS fibre was used to study the relationship between the fibre quality and exciton recombination kinetics; as shown in Fig. S7, it is a three-exponential decay function:

$$I_{(t)} = A_1 \exp\left(-\frac{t-t_0}{\tau_1}\right) + A_2 \exp\left(-\frac{t-t_0}{\tau_2}\right) + A_3 \exp\left(-\frac{t-t_0}{\tau_3}\right) \quad (1)$$

$$\tau_{ave} = \frac{A_1 \tau_1^2 + A_2 \tau_2^2 + A_3 \tau_3^2}{A_1 \tau_1 + A_2 \tau_2 + A_3 \tau_3} \tag{2}$$

where τ_1 is the short-lived PL lifetime, τ_2 is the intermediate PL lifetime and τ_3 is the long-lived PL lifetime. Their average decay lifetime is calculated to be 51.7 ns according to Eqns (1) and (2). Compared to the previously reported value (*ca* 16.3 ns),^{23,24} the average lifetime of MAPbBr₃@PS fibre is significantly increased. At the same time, the longer the lifetime, the less the defect state of the material, which is mainly attributed to the excellent



Figure 2. (a), (b) Top view SEM images of MAPbBr₃@PS fibres at different magnifications; (c) SEM cross-section diagram of MAPbBr₃@PS fibres; (d) TEM image of MAPbBr₃@PS fibres.

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Figure 3. (a) Variation of PL peak strength of MAPbBr₃@PS fibres (PS-1) and MAPbBr₃@PS films (PS-2) after immersing in water for different times; note that the value of the PL peak strength is the result of statistics from more than 10 curves. The photographs show MAPbBr₃@PS films after immersing in water under 365 UV light for 0 day and 30 days. (b) PL intensity of PS-1 and PS-2 at 95 °C. (c) The PL intensity under oxygen and (d) a 365 nm UV lamp, respectively.



Figure 4. (a) IR spectra of PS fibre and MAPbBr₃@PS fibre, in which the peak at 1560 cm⁻¹ corresponds to the deformation vibration of N–H and the peak at 3100 cm⁻¹ corresponds to the stretching vibration of C–H. The insets show enlarged views. (b) The model diagram of hydrogen bonds between MAPbBr₃ and PS.

protection of PS for MAPbBr₃. Further, by adjusting the mixing ratio of the MAX (X \equiv I, Br, Cl) and PbX₂ in the precursor solution, fibres covering the entire spectral range can be achieved (Figs S8 and S9).

It is well known that perovskite materials are extremely sensitive to water, heat, oxygen and light, which highly limits their applications. Equations (3)–(6) reveal the degradation mechanism of



Figure 5. (a) Schematic diagram of the configuration of the LED device; (b) EL spectrum of the LED lamp under 3 V forward bias voltage, with photographs; (c) the CIE chromaticity diagram of the fabricated white LED device; (d) the EL spectra of the LED device at different voltages.

perovskite under water and in heat, oxygen and light conditions, respectively:

 $4CH_{3}NH_{3}PbBr_{3}+2H_{2}O \rightarrow (CH_{3}NH_{3})_{4}PbBr_{6}.2H_{2}O+3PbBr_{2} \quad (3)$

$$CH_3NH_3PbBr_3 \stackrel{\Delta}{\leftrightarrow} CH_3NH_2 + HBr + PbBr_2$$
(4)

$$CH_3NH_3PbBr_3 \leftrightarrow MABr + PbBr_2$$
 (5)

$$2MABr \xrightarrow{hv,O_2} 2CH_3NH_2 + H_2O + Br_2$$
(6)

In this work, the stabilities of MAPbBr3 are significantly improved by the electrospinning process with PS. Here, an MAPbBr3@PS film sample prepared by the electrospinning technique (PS-1) was used as the contrast with a film prepared by spin coating (PS-2).²⁵⁻²⁹

In order to investigate the stability of the sample in water, PS-1 and PS-2 were separately soaked in distilled water and their fluorescence intensity was regularly monitored. The corresponding fluorescence intensity statistics are shown in Fig. 3(a). The fluorescence intensity of PS-1 decreases slowly with time, and 70% is maintained after soaking in water for 30 days. But the fluorescence intensity for PS-2 decreases significantly. In another experiment, the irradiated MAPbBr₃@PS film emits green fluorescence when excited by a UV lamp, not only before but also after soaking in water for 30 days, showing excellent stability in water. The thermal stability of MAPbBr₃@PS film was also detected by the same method. As shown in Fig. S10, the fluorescence intensity of PS-1 can be maintained at more than 90% after heating to 95 °C and can be recovered after cooling. However, the fluorescence intensity of PS-2 is less than 70% only. In addition, the time stability of the MAPbBr₃@PS film was also explored at the glass transition temperature (*ca* 95 °C) of PS. As shown in Fig. 3(b), 85% of the fluorescence strength of PS-1 is retained after leaving at 95 °C for 350 min, but only 30% for PS-2. As shown in Fig. 3(c), for PS-1 more than 90% of the fluorescence intensity is kept after leaving in pure oxygen for 10 days, whereas there is a significant drop for PS-2. Thus the excellent stability for MAPbBr₃@PS nanofibre film under water, at high temperature and in oxygen can be confirmed.

The light stability of MAPbBr₃@PS is also rather important because of its extensive use in photodetectors and light-emitting devices. As shown in Fig. 3(d), more than 90% of the fluorescence intensity for PS-1 is retained after irradiating with UV light for 100 h, but less than 60% for PS-2. Thus the PS fibre has an excellent photoprotection effect on MAPbBr₃ nanocrystals.

The excellent stability of the MAPbBr₃@PS fibre film is due not only to the spatial effect of MAPbBr₃ and the hydrophobicity of PS fibre but also to the formation of hydrogen bonds between the MAPbBr₃ crystal and the PS fibre. As shown in the IR spectrum of Fig. 4(a), the IR vibrating peaks at 3100 and 1560 cm⁻¹ of the MAPbBr₃@PS fibre membrane have a significant redshift and an increase in the half-peak width compared with the PS fibre membrane, which proves the formation of hydrogen bonds between MAPbBr₃ crystals and PS fibres.^{30,31} The 3100 cm⁻¹ vibrating peak corresponds to the C–H vibration of benzene,^{32,33} and the 1560 cm⁻¹ vibrating peak corresponds to the N–H vibration of the methylamine group,^{34,35} so that C–H···Br and N–H··· π can be formed between the PS and MAPbBr₃ crystals,^{9,36,37} which can improve the stability of the perovskite (Fig. 4(b)).

White LEDs based on MAPbBr₃@PS fibre film were fabricated on an InGaN LED chip, which was obtained from commercial ((Sr, Ca) AlSiN₃:Eu²⁺) phosphor ($\lambda_{max} = 450$ nm) (Fig. 5(a)).^{18,38} The electroluminescence (EL) spectroscopy and image under 3 V forward bias voltage are shown in Fig. 5(b). It can be seen that the LED lamp obtained exhibits bright white light with a correlated colour temperature (CCT) of 6322 K, a colour rendering index (Ra) of 88 and a CIE (Commission International de L'Eclairage) chromaticity coordinate of (0.3161, 0.3241) (Fig. 5(c)). The EL spectral intensity increases with increase of the forward bias voltage from 3 to 4 V. However, it is relatively stable in shape and position as shown in Fig. 5(d), which fully demonstrates the application of MAPbBr₃@PS film in LED and liquid crystal display backlight colour conversion.

CONCLUSIONS

In summary, we prepared superhydrophobic PS@MAPbBr₃ nanofibre film by the electrospinning technology. The PL properties were first investigated by introducing a trace of perovskite crystals. At the same time, the illumination range of the OMHP@polymer fibre membrane can cover the whole visible range by adjusting the proportion of halides in the perovskite molecule. More importantly, they exhibit excellent stability in water, heat, oxygen and light. The CIE colour coordinates are (0.3161, 0.3241), and the CCT of LEDs based on MAPbBr₃@PS fibre is 6322 K, which is close to sunlight (the colour rendering index Ra is 88). This work is of great significance not only to the application of perovskite, a metal–organic halide, in new fields such as colour conversion but also to the application of polymers in the field of PL.

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SUPPORTING INFORMATION

Supporting information may be found in the online version of this article.

REFERENCES

- 1 Wang P, Zhang X, Zhou Y, Jiang Q, Ye Q, Chu Z *et al.*, *Nat Commun* **9**: 2225 (2018).
- 2 Wang Z, Lin Q, Wenger B, Christoforo MG, Lin Y-H, Klug MT et al., Nat Energy **3**:855–861 (2018).

- 3 Oksenberg E, Sanders E, Popovitz-Biro R, Houben L and Joselevich E, Nano Lett 18:424–433 (2018).
- 4 Yang Z, Deng Y, Zhang X, Wang S, Chen H, Yang S *et al., Adv Mater* **30**: 1704333 (2018).
- 5 Lin K, Xing J, Quan LN, de Arquer FPG, Gong X, Lu J *et al.*, *Nature* **562**: 245–248 (2018).
- 6 Cao Y, Wang N, Tian H, Guo J, Wei Y, Chen H *et al.*, *Nature* **562**:249–253 (2018).
- 7 Niu G, Guo X and Wang L, J Mater Chem A 3:8970–8980 (2015).
- 8 Berhe TA, Su W-N, Chen C-H, Pan C-J, Cheng J-H, Chen H-M *et al.*, *Energ Environ Sci* **9**:323–356 (2016).
- 9 Huang F, Li M, Siffalovic P, Cao G and Tian J, *Energ Environ Sci* **12**: 518–549 (2019).
- 10 von Hauff E, Lira-Cantu M, Brown TM and Hoppe H, Adv Energ Mater 5: 1501924 (2015).
- 11 Stec AA and Hull TR, Energ Buildings 43:498-506 (2011).
- 12 Jelle BP, Energ Buildings 43:2549–2563 (2011).
- 13 Kurekci NA, Energ Buildings 118:197-213 (2016).
- 14 Khoukhi M, Fezzioui N, Draoui B and Salah L, *Appl Therm Eng* **105**:669–674 (2016).
- 15 Bao JB, Liu T, Zhao L, Hu GH, Miao XR and Li XH, *Polymer* **53**:5982–5993 (2012).
- 16 Gu HB, Ma C, Liang CB, Meng XD, Gu JW and Guo ZH, J Mater Chem C 5: 4275–4285 (2017).
- 17 Tsai PC, Chen JY, Ercan E, Chueh CC, Tung SH and Chen WC, *Small* 14: e1704379 (2018).
- 18 Liao H, Guo SB, Cao S, Wang L, Gao FM, Yang ZB *et al., Adv Opt Mater* **6**: 1800346 (2018).
- 19 Zhou Y, You L, Wang S, Ku Z, Fan H, Schmidt D *et al., Nat Commun* **7**: 11193 (2016).
- 20 Saidaminov MI, Abdelhady AL, Murali B, Alarousu E, Burlakov VM, Peng W *et al.*, *Nat Commun* **6**:7586 (2015).
- 21 Chen Z, Dong Q, Liu Y, Bao C, Fang Y, Lin Y *et al.*, *Nat Commun* **8**:1890 (2017).
- 22 Jin Z, Gehrig D, Dyer-Smith C, Heilweil EJ, Laquai F, Bonn M et al., J Phys Chem Lett **5**:3662–3668 (2014).
- 23 Huang S, Li Z, Kong L, Zhu N, Shan A and Li L, J Am Chem Soc 138: 5749–5752 (2016).
- 24 Longo G, Pertegás A, Martínez-Sarti L, Sessolo M and Bolink HJ, J Mater Chem C 3:11286–11289 (2015).
- 25 Abdelmageed G, Mackeen C, Hellier K, Jewell L, Seymour L, Tingwald M et al., Sol Energ Mater Sol Cells 174:566–571 (2018).
- 26 Christians JA, Miranda Herrera PA and Kamat PV, J Am Chem Soc 137: 1530–1538 (2015).
- 27 Aristidou N, Sanchez-Molina I, Chotchuangchutchaval T, Brown M, Martinez L, Rath T et al., Angew Chem Int Ed 54:8208–8212 (2015).
- 28 Yang J, Siempelkamp BD, Liu D and Kelly TL, ACS Nano 9:1955–1963 (2015).
- 29 Vickers ET, Graham TA, Chowdhury AH, Bahrami B, Dreskin BW, Lindley S et al., ACS Energ Lett **3**:2931–2939 (2018).
- 30 Taylor LS and Zografi G, Pharm Res 14:1691-1698 (1997).
- 31 Pinilla S, Barrio R, González N, Pérez Casero R, Márquez F, Sanz JM et al., J Phys Chem C **122**:22667–22674 (2018).
- 32 Xu J, Wu Z, Wan H, Deng G, Lu B, Eckhardt AK *et al., J Am Chem Soc* **140**: 9972–9978 (2018).
- 33 Dewar MJS and Komornicki A, J Am Chem Soc **99**:6174–6179 (1977).
- 34 Kuriakose S, Vijayan KK, Shaji S, Eappen SM, Nair KPR and Rasheed TMA, *Spectrochim Acta Part A* **60**:2283–2286 (2004).
- 35 Zeng X, Beckers H and Willner H, Angew Chem Int Ed **52**:7981–7984 (2013).
- 36 Yan XQ, Zhao XR, Wang H and Jin WJ, J Phys Chem B **118**:1080–1087 (2014).
- 37 Wang H, Wang W and Jin WJ, Chem Rev 116:5072-5104 (2016).
- 38 Luo D, Wang L, Or SW, Zhang H and Xie RJ, *RSC Adv* **7**:25964–25968 (2017).