科学通报 2022 年 第 67 卷 第 24 期: 2958 ~ 2964
电子科技大学功能材料与应用化学专辑 论 文
《中国科学》杂志社 SCIENCE CHINA PRESS

柔性显示一体集成的热释电自供能悬浮触控传感阵列

王凯伦[1,3], 胡潇然[1,3], 孙阔[2,3], 夏亮[2,3], 张千[1,3], 向勇[1,3*]

1. 电子科技大学材料与能源学院, 成都 611731;
2. 成都京东方光电科技有限公司, 成都 611731;
3. 四川省柔性显示材料基因组工程研究中心, 成都 611731
* 联系人, E-mail: Xiang@uestc.edu.cn

2022-01-05 收稿, 2022-02-23 修回, 2022-04-24 接受, 2022-04-29 网络版发表

摘要 随着智能移动终端的迅速发展, 人们对人机交互体验有了更高的要求. 但是, 当前基于外置机械系统、摄像头、红外线或毫米波等技术的人机交互方案还存在着诸多不足, 如便携性差、功耗偏高、识别误判等, 并且识别器件与显示器件难以一体集成, 需要占据额外的空间, 不利于移动终端的轻薄化发展. 本文报道了一种基于红外热释电材料偏氟乙烯共聚物制备的自供能、高透过率悬浮触控传感阵列, 该传感阵列能够与显示器件一体化集成, 具有较高的透光率(≥90%)和较小的厚度(数十微米), 以及针对不同距离与运动速度的手势识别功能. 基于该类红外热释电薄膜器件的阵列传感技术有望支撑未来电子产品轻薄化以及多功能显示模组集成发展.

关键词 聚偏二氟乙烯-三氟乙烯, 悬浮触控, 极化, 人机交互, 柔性显示

随着智能移动终端的快速普及, 人们对人机交互的便携性和有效性要求越来越高. 人机交互研究方向之一是提高终端产品与客户间交互能力, 目前主要通过触摸控制、声音识别、视觉跟踪以及悬浮触控等方式实现. 悬浮触控作为一种利用非接触肢体运动实现交互信息输入的技术手段, 在智能手机、平板电脑和车载屏幕等领域具有广阔的应用前景. 目前悬浮触控技术主要通过外置机械系统、摄像头、红外线和毫米波等手段实现[1]. 其中, 外置机械系统通过佩带额外设备检测运动并向用户提供反馈信息, 但这会影响移动终端的便携性, 降低用户体验[2]. 基于摄像头的交互系统通常会受到视野和外形因素的限制, 使得它们无法检测位于屏幕附近的物体运动. 此外, 摄像头传感器对环境依赖性强, 例如环境色彩、拍摄角度及手势运动速度等都会影响其识别的准确率[3~6]. 红外线传感器虽然能检测距离较远的肢体运动, 但红外线发射和接收装置尺寸较大且功耗较高[7,8]. 基于毫米波的传感器可以达到较高识别精度, 但毫米波在空气中衰减严重, 因此识别距离较为有限[9]. 通常情况下, 悬浮触控传感器需要配合显示器件来实现信息输入后的反馈, 但上述器件均不具备高度透明及柔性可折叠的特性, 难以与显示器件一体集成, 需要占用显示区域并增加产品功耗. 因此, 随着智能移动终端的高速发展, 高度集成化和轻薄化所要求的功耗与空间限制对传感器的自供能、柔性化以及易与显示器件一体集成等特性有了更高要求.

上述需求有望通过新型热释电聚合物传感器实现. 热释电聚合物传感器是利用聚合物(如聚偏氟乙烯及其共聚物等)的热释电效应, 通过外部热源引起热释电聚合物自发极化强度发生改变从而产生感应电荷的传感器[10]. 在以往的研究中, 研究者开发了一系列非接触式热释电传感器. Zhang等人[11]利用聚偏二氟乙烯(polyvinylidene difluoride, PVDF)薄膜制备一种柔性热释电发生器, 其可以收集环境中的废热来驱动显示器

引用格式: 王凯伦, 胡潇然, 孙阔, 等. 柔性显示一体集成的热释电自供能悬浮触控传感阵列. 科学通报, 2022, 67: 2958–2964
Wang K L, Hu X R, Sun K, et al. Flexible display integrated pyroelectric self-powered floating touch sensor array (in Chinese). Chin Sci Bull, 2022, 67: 2958–2964, doi: 10.1360/TB-2022-0016

件. Cao等人[12]利用PVDF制备可用于声音功率测量的热释电器件. Marchiori等人[13]以聚偏二氟乙烯-三氟乙烯(poly(vinylidene difluoride-trifluoroethylene), PVDF-TrFE)作为热释电材料, 开发了一种具有温度和红外传感功能的可伸缩电子皮肤. Roy等人[14]通过静电纺丝制备PVDF/氧化石墨烯(graphene oxide, GO)纳米纤维, 可用来监测呼吸过程中的温度波动. Cook等人[15]将热释电聚合物PVDF制备的传感器用于检测液滴结冰时放出的热量, 可以快速、自动地计算冻结比例曲线和成核速率. Pullano等人[16]利用PVDF薄膜与红外源结合制成接触式温度传感器快速监测生物流体的局部温度. 上述研究表明, 热释电聚合物能够灵敏地感知外部环境温度变化. 故从可行性上分析, 热释电聚合物可以识别到人肢体运动时的温度变化并反馈电信号, 从而实现悬浮触控功能. 相较前述的悬浮触控技术, 热释电聚合物传感器具有高透明、可折叠及自供能的特点, 并且可实现与大面积显示器件的一体集成.

然而, 目前尚无热释电悬浮触控传感器的相关研究报道, 主要是因为大面积热释电聚合物的均匀制备工艺尚不成熟; 另外, 热释电聚合物的热释电特性依赖强电场诱导偶极取向, 为提高极化效率往往会升高极化电压, 但过高电压会造成显示器件损坏. 在本研究中, 我们选用PVDF-TrFE作为热释电聚合物材料, 通过自主设计的极化设备利用较低的极化电压可实现良好的极化效果, 降低基板被高电压损坏的概率. 目前, 所制备的薄膜最大面积可达300 mm×330 mm, 透过率可达到90%以上, 最大识别距离可达100 mm.

1 实验

(ⅰ) PVDF-TrFE热释电传感器的制备. 图1展示了热释电传感器的制备流程. 首先将PVDF-TrFE粉末(购买自PIEZOTECH公司)与丁酮(购买自Sigma-Aldrich公司)按1:10(质量比)均匀混合, 室温密封条件下使用磁力搅拌器搅拌6 h形成均匀溶液. 使用涂布机以刮涂的方式将溶液以440 μm厚度均匀涂布在显示器件上, 烘干后形成20 μm聚合物薄膜. 再将薄膜置于烘箱中140°C退火30 min以提高薄膜结晶度. 使用极化设备对薄膜进行极化处理. 最后在薄膜表面涂布一层纳米银线电极, 再使用光学胶将聚对苯二甲酸乙二酯(polyethylene glycol terephthalate, PET)薄膜贴附在传感器表面对其进行封装.

(ⅱ) 测试方法. 利用BrukerAXS D8 AdvanceX射线衍射仪表征聚合物结晶性能, 管电流为40 mA, 管电压为40 kV, 使用Cu辐射, 扫描速度为10(°)/min, 测试范围为10°~80°. 聚合物压电系数d_{33}通过型号为YE2730A准静态测试仪进行表征. 热释电传感器的电压信号可通过NI9238电压采集卡采集, 采样区间为±0.5 V, 采样率为50 kHz.

2 结果与讨论

热释电聚合物通常需要强电场诱导偶极取向, 从而获得热释电特性. 传统电晕极化利用钨针丝尖端放电产生强电场诱导偶极取. 为提高极化效率, 该极化方案需要施加高至1.8万伏的电压[17~21]. 但过高的电压很容易损坏显示模组基底. 为解决该问题, 我们设计了低电压极化方案, 设备结构如图2(a)所示. 设备通过水平阵列化排列的金属丝放电, 源极电压为–5000 V, 栅极电压为–3000 V. 该方案在提高极化效率时不需要大幅度提高极化电压. 极化过程中产生的负电荷会沿电场方向均匀沉积到薄膜上表面形成虚拟电极, 直至薄膜上表面电势与栅极一致. 由于薄膜厚度一般为10~30 μm且下表面接地, 故可在薄膜内形成一个约100~300 V/μm的电场. 薄膜中的偶极在该电场作用下定向排列, 从而实现极化. 极化时间可缩短至5 min. 该极化方案不仅解决了大面积薄膜均匀制备的问题, 还在提高极化效率的同时显著降低了显示器件被高电压

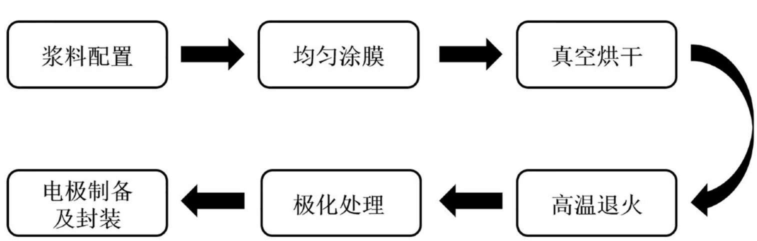

图 1 热释电传感器制备流程图
Figure 1 Preparation flow chart of pyroelectric sensor

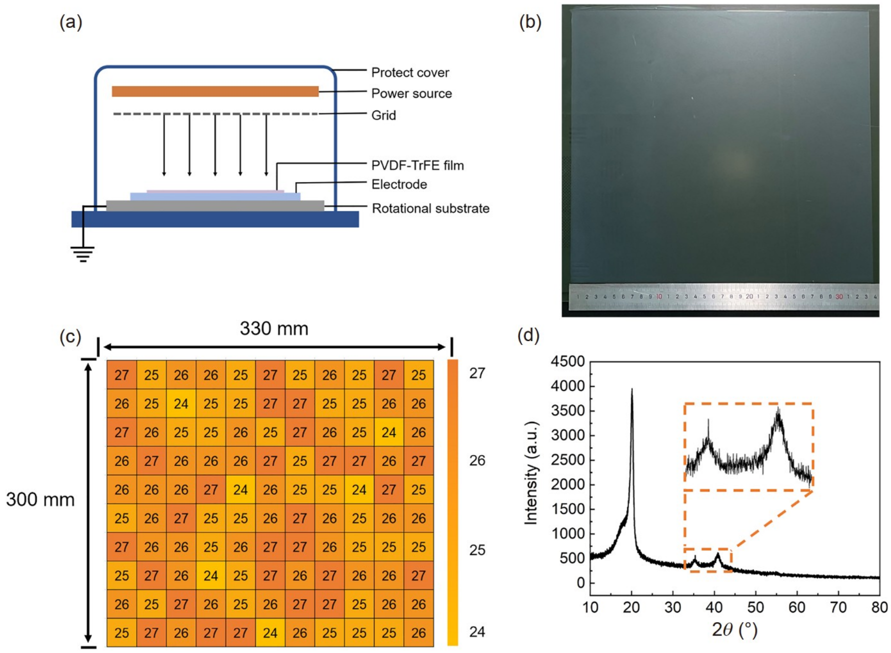

图 2 (网络版彩色)制备薄膜使用的极化设备结构和薄膜压电性能及结晶行为. (a) 极化设备结构; (b) 均匀制备的大面积薄膜; (c) 大面积薄膜的d_{33}分布; (d) 聚合物薄膜的XRD图

Figure 2 (Color online) The structure of the polarized device used in the preparation of films and the crystalline behavior and piezoelectric properties of the films. (a) Polarized device structure; (b) uniformly prepared large-area film; (c) d_{33} distribution of the large-area film; (d) XRD pattern of the polymer film

损坏的概率. 图2(b), (c)展示了我们制备的300 mm×330 mm热释电聚合物薄膜以及薄膜d_{33}压电系数分布, 压电系数≥25 pC/N, 均匀度在25±2 pC/N以内.

据文献[22,23]报道, 向偏氟乙烯中引入三氟乙烯单体, 可增加分子链空间位阻, 有利于实现C-F偶极定向取向, 提高剩余极化强度, 从而提高聚合物热释电性能. 由于释电聚合物的热释电性能直接影响了传感器性能, 所以我们选用PVDF-TrFE材料来制备传感器. PVDF-TrFE聚合物中主要为拥有极性晶体结构的β相晶体, 可以表现出较强的热释电性能. 图2(d)是厚度为20 μm的PVDF-TrFE薄膜X射线衍射图谱. 位于20.0°、35.2°和40.8°的衍射峰对应β相晶体的(110)/(200)、(001)和(201)晶面[24,25]. 通过分峰分析和计算, 聚合物中β相晶体的结晶度为80%. 因此, 该聚合物材料应具有较强的热释电性能.

室温环境下, 我们用该PVDF-TrFE聚合物材料制备了10、20、30 μm三种不同厚度的薄膜. 聚合物薄膜透光率如图3(a)所示, 在550 nm波长处, 10与20 μm薄膜透光率达到90%以上, 满足在显示器件上应用的要求. 在相同条件下, 我们对不同厚度薄膜进行热释电峰值信号的测试, 测试环境如图3(b)所示. 器件的形态及膜层结构如图3(c)所示. 透过整个器件仍能够清晰地看到背部的字体. 图3(d)表明随着薄膜厚度增加, 热释电信号峰值也相应增加, 这可能是因为薄膜厚度越大, 电容相应减小, 在产生相同电荷量条件下电压升高. 综合透光率和热释电信号测试结果, 我们认为20 μm是制备热释电传感器的最佳薄膜厚度.

我们通过改变热源移动速度和热源与传感器间的距离来探究上述变量对热释电信号的影响. 将热源固定在三维台上, 通过调整坐标参数使热源分别以50、100、150 mm/s速度在垂直距离为10 mm条件下水平移动对传感器进行测试. 图4(a)~(c)表明热源移动速度越快, 传感器产生的热释电信号越大. 固定三维台移动速度, 调整坐标改变热源与传感器距离, 在速度为150 mm/s条件下, 垂直距离分别为100、50、10 mm. 测得热释电信号如图4(d)~(f)所示. 实验证明热源距离传感器越近, 产生的热释电信号就越强. 以上结果表明, 热释电信号强度与热源移动速度和行程距离呈正相关.

最后, 我们将制备的传感阵列与成都京东方光电

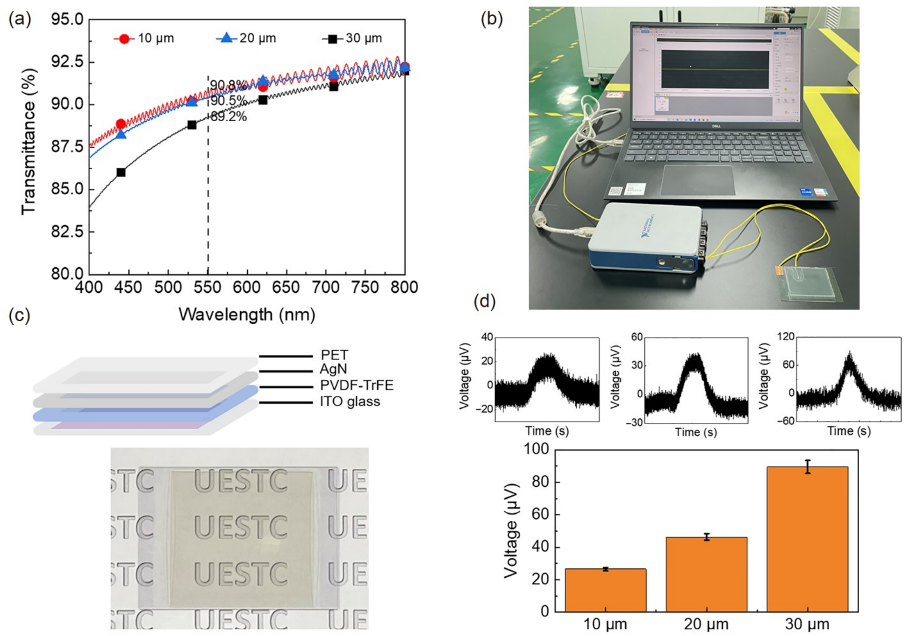

图 3 (网络版彩色)通过薄膜的光学性能及热释电性能确定薄膜最优厚度. (a) 不同厚度聚合物薄膜透光率. (b) 器件的测试环境. (c) 器件的实物图. (d) 不同厚度薄膜的热释电峰值电压

Figure 3 (Color online) The optimal thickness of the film was determined by its optical properties and pyroelectric properties. (a) Transmittance of polymer films with different thicknesses. (b) Test environment of the device. (c) Physical image of the device. (d) Pyroelectric peak voltage of films with different thicknesses

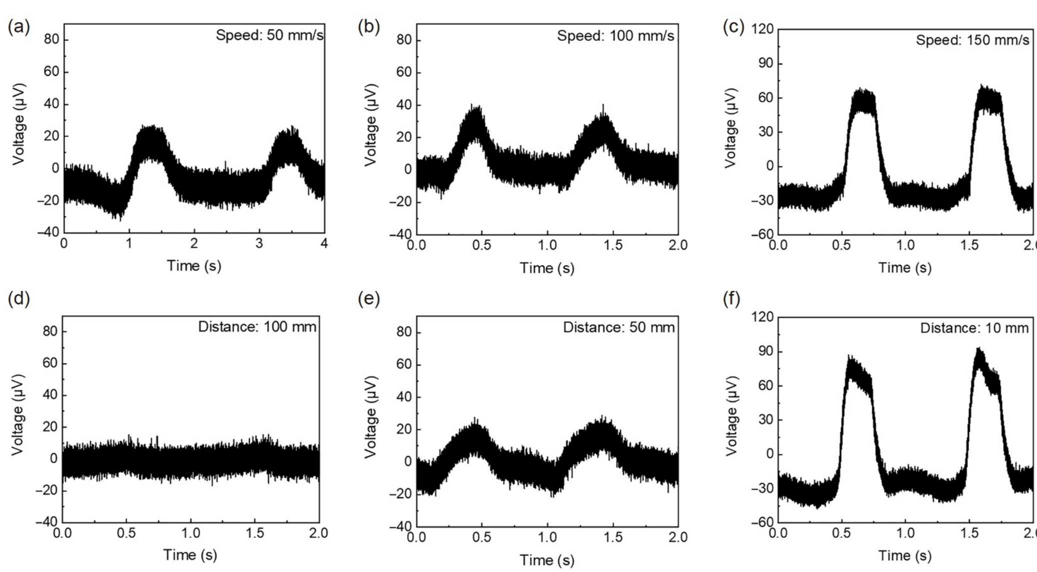

图 4 通过控制变量法研究热源移动速度和热源与传感器间距离对传感器热释电信号的影响. 热源距离传感器10 mm, 移动速度为50(a)、100(b)、150(c) mm/s时产生的热释电信号. 热源距离传感器100(d)、50(e)、10(f) mm, 移动速度为150 mm/s时产生的热释电信号

Figure 4 The influence of the moving speed of the heat source and the distance between the heat source and the device on the pyroelectric signal of the device was studied by the control variable method. The pyroelectric signal generated when the distance between the heat source and the device is 10 mm and the moving speed is 50 (a), 100 (b), and 150 (c) mm/s. The pyroelectric signal generated when the distance between the heat source and the device is 100 (d), 50 (e), and 10 (f) mm and the moving speed is 150 mm/s

科技有限公司提供的8英寸(1英寸=2.54 cm)可折叠屏幕模组集成. 如图5(a)所示, 当屏幕弯折时我们制备的薄膜仍能贴附在屏幕上并随着屏幕的弯折而弯折. 图5(b)是集成传感器的膜层结构示意图. 将传感阵列集成到

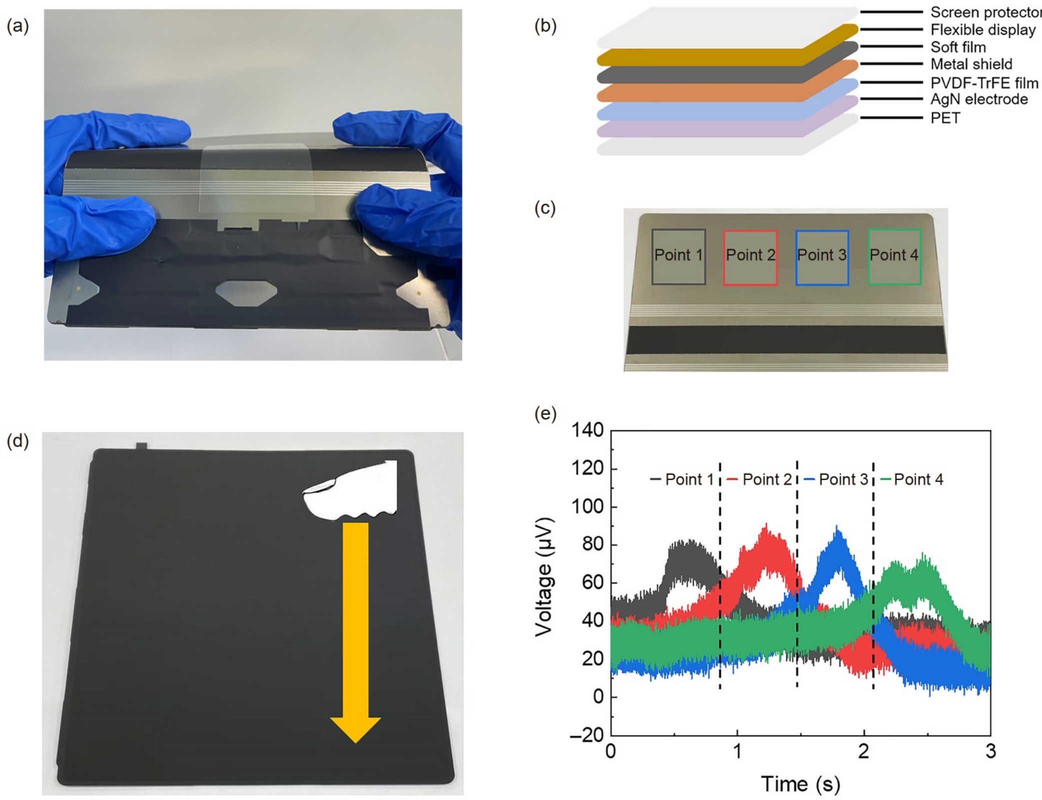

图 5 (网络版彩色)热释电传感器阵列化集成到屏幕模组并测试其热释性能. (a) 薄膜与折叠屏模组集成. (b) 集成传感器膜层结构. (c) 传感器阵列化结构示意图. (d) 手指运动轨迹. (e) 阵列化传感器信号图

Figure 5 (Color online) The pyroelectric device is integrated into the screen module in an array and its pyroelectric performance is tested. (a) Film and folding screen module integration. (b) Membrane structure of integrated sensors. (c) Schematic diagram of the sensor array structure. (d) Finger movement track. (e) Signal diagram of arrayed sensor

屏幕背板(图5(c), 手指置于屏幕上方垂直距离1 cm位置水平移动, 运动轨迹如图5(d)所示. 最后测得各个阵点随时间变化输出的电压信号, 然后绘制出图5(e)所示的信号图(从左至右依次为point 1~point 4). 随着手指依次经过每个阵点, 每个阵点都会输出一个峰值电压, 这样就将手指的运动轨迹通过电信号的形式记录下来.

3 结论

本文制备的PVDF-TrFE柔性热释电传感阵列能够对不同移动速度和距离的热源反馈不同强度的电信号, 实现悬浮触控的功能, 其最大的识别距离可达100 mm. 该传感阵列可与手机屏幕一体集成, 实现对手指移动产生热释电信号的检测, 且不影响折叠屏的弯曲特性. 此外, 本文制备的热释电薄膜透光率可达90%以上. 在后续研究中, 我们希望将其集成到屏幕发光层上方, 进一步提高传感阵列灵敏度. 希望后续通过对热释电PVDF-TrFE传感阵列的持续研发能够为电子产品轻薄化以及显示屏幕多功能集成贡献一份力量.

参考文献

1 Wang G Z, Huang Y P, Chang T S, et al. Bare finger 3D air-touch system using an embedded optical sensor array for mobile displays. J Display Technol, 2014, 10: 13–18

2 Feiner S, MacIntyre B, Höllerer T, et al. A touring machine: Prototyping 3D mobile augmented reality systems for exploring the urban environment. Pers Technol, 1997, 1: 208–217

3 Schlömer T, Poppinga B, Henze N, et al. Gesture recognition with a Wii controller. In: TEI '08: Proceedings of the 2nd International Conference on

Tangible and Embedded Interaction. 2008. 11–14
4 Valkov D, Steinicke F, Bruder G, et al. 2D touching of 3D stereoscopic objects. In: 29th Annual Chi Conference on Human Factors in Computing Systems. 2011. 1353–1362
5 Morrison G. A camera-based input device for large interactive displays. IEEE Comput Graph Appl, 2005, 25: 52–57
6 Tian J, Zhang W, Zhang T, et al. Research status of gesture recognition based on vision: A review. IOP Conf Ser Earth Environ Sci, 2015, 632: 042019
7 Nogales R E, Benalcázar M E. Hand gesture recognition using machine learning and infrared information: A systematic literature review. Int J Mach Learn Cyber, 2021, 12: 2859–2886
8 Liang F, Cai C, Zhang K, et al. Infrared gesture recognition system based on near-sensor computing. IEEE Electron Device Lett, 2021, 42: 1053–1056
9 Lien J, Gillian N, Karagozler M E, et al. Soli: Ubiquitous gesture sensing with millimeter wave radar. ACM Trans Graph, 2016, 35: 1–19
10 Ruan L, Yao X, Chang Y, et al. Properties and applications of the β phase poly(vinylidene fluoride). Polymers, 2018, 10: 1–27
11 Zhang H, Xie Y, Li X, et al. Flexible pyroelectric generators for scavenging ambient thermal energy and as self-powered thermosensors. Energy, 2016, 101: 202–210
12 Cao Y, Chen Q, Zheng H, et al. Study on the mechanism of ultrasonic power measurement sensor based on pyroelectric effect. Acoust Phys, 2018, 64: 789–795
13 Marchiori B, Regal S, Arango Y, et al. PVDF-TrFE-based stretchable contact and non-contact temperature sensor for E-skin application. Sensors, 2020, 20: 623
14 Roy K, Ghosh S K, Sultana A, et al. A self-powered wearable pressure sensor and pyroelectric breathing sensor based on GO interfaced PVDF nanofibers. ACS Appl Nano Mater, 2019, 2: 2013–2025
15 Cook F, Lord R, Sitbon G, et al. A pyroelectric thermal sensor for automated ice nucleation detection. Atmos Meas Tech, 2020, 13: 2785–2795
16 Pullano S A, Mahbub I, Islam S K, et al. PVDF sensor stimulated by infrared radiation for temperature monitoring in microfluidic devices. Sensors, 2017, 17: 850
17 Tansel T, Ener R S, Rusen A. Uniform, large surface-area polarization by modifying corona-electrodes geometry. Rev Sci Instrum, 2013, 84: 015107
18 Kim K, Seomoon K. A study on the corona-treated PVdF films with alkyl methacrylate monomer as a coupling agent. J Ind Eng Chem, 2017, 47: 150–153
19 Kim H, Torres F, Wu Y, et al. Integrated 3D printing and corona poling process of PVDF piezoelectric films for pressure sensor application. Smart Mater Struct, 2017, 26: 085027
20 Mohammadizadeh M, Yousefi A A. Deposition of conductive polythiophene film on a piezoelectric substrate: Effect of corona poling and nano-inclusions. Iran Polym J, 2016, 25: 415–422
21 Xi Y, Fan H, Li W, et al. Effect of corona poling on structure evolutions of α-phase and β-phase PVDF films. Proc SPIE, 2010, 7658: 765852
22 Al Abdullah K, Batal M A, Hamdan R, et al. The enhancement of PVDF pyroelectricity (pyroelectric coefficient and dipole moment) by inclusions. Energy Procedia, 2017, 119: 545–555
23 Fonseca L, Prunnila M, Peiner E, et al. Comparative assessment of PVDF and PVDF-TrFE piezoelectric polymers for flexible actuators applications. SPIE Conf Ser, 2017, 10246: 102460N
24 Tanaka R, Tashiro K, Kobayashi M. Annealing effect on the ferroelectric phase transition behavior and domain structure of vinylidene fluoride (VDF)-trifluoroethylene copolymers: A comparison between uniaxially oriented VDF 73% and 65% copolymers. Polymer, 1999, 40: 3855–3865
25 Oliveira F, Leterrier Y, Månson J A, et al. Process influences on the structure, piezoelectric, and gas-barrier properties of PVDF-TrFE copolymer. J Polym Sci Part B-Polym Phys, 2014, 52: 496–506

Summary for “柔性显示一体集成的热释电自供能悬浮触控传感阵列”

Flexible display integrated pyroelectric self-powered floating touch sensor array

Kailun Wang[1,3], Xiaoran Hu[1,3], Kuo Sun[2,3], Liang Xia[2,3], Qian Zhang[1,3] & Yong Xiang[1,3*]

[1] *School of Materials and Energy, University of Electronic Science and Technology of China, Chengdu 611731, China;*
[2] *Chengdu BOE Optoelectronics Technology Co., Ltd., Chengdu 611731, China;*
[3] *Sichuan Flexible Display Materials Genome Engineering Research Center, Chengdu 611731, China*
* Corresponding author, E-mail: Xiang@uestc.edu.cn

With the rapid development of smart electronic devices, the portable terminals are expected to operate under higher convenience and effectiveness of the input and feedback. Thus, human-computer interaction technology, including the directions input by touch control, voice recognition, visual tracking, and floating touch, is proposed to realize contact and non-contact information input. By integrating the human-computer interaction technology with the display devices, the user experience of the portable terminals can be largely improved. However, as a branch of human-computer interaction technology, floating touch suffers from several issues that impede its development in recognition, energy-efficiency, and portability. For example, the camera is susceptible to the surrounding environment of the recognized object, impacting the recognition accuracy of the sensor; the sensing distance of the millimeter wave sensor is limited by the attenuation phenomenon during the transmission of millimeter wave in the air; the transmitting devices and receiving devices of infrared sensor require high power consumptions, leading to increased energy use of the total portable terminals; the components are difficult to integrate with the flexible screen due to the large space they occupied and additional mechanical system, hampering the design of thin structure of the sensor. In this work, a PVDF-TrFE based flexible pyroelectric sensor is proposed to realize floating touch with portable, self-powered, and accurate recognition functions. Large-area pyroelectric PVDF-TrFE thin film with high uniformity is polarized via our self-designed polarization equipment, which significantly improves the polarization efficiency under low voltage conditions. The maximum polarization area can reach 300 mm×330 mm. In the experiment, we firstly compare the pyroelectric performance and light transmittance of films of different thicknesses. The optimal thickness of the PVDF-TrFE thin film is screened out to be 20 μm according to various indicators. Then the influence of movement speed and the distance of the heat source on the intensity of the responsive pyroelectric signal are studied. The results show that our sensor can not only recognize different speeds and feedback signals of different intensities, but also recognize different distances of the heat source. The farthest recognition distance is up to 100 mm. More importantly, our sensor has a small volume and thickness of only tens of micrometers. Such small occupancy leaves more spaces for integrating with display devices. The sensor also can be operated without external power supply, reducing the power consumption of the total mobile terminal. At present, we integrate the pyroelectric sensor under the metal layer of the display device. Across the whole display module, our sensor can still detect the limb movement track above the screen and record it in the form of electrical signal. Due to high transmittance which is up to 90% of the PVDF-TrFE film, our sensor is expected to lift above the light-emitting layer when integrating with a display device. This can further increase the detection distance, the sensitivity, and strength of the feedback signal. The proposed flexible PVDF-TrFE based sensor will have a broader application prospect in the fields of light and thin electronic products and multi-function integration of display screens.

PVDF-TrFE, floating touch, polarization, human-computer interaction, flexible display

doi: 10.1360/TB-2022-0016