用于神经形态计算的CsPbBr₃钙钛矿忆阻器性能研究

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摘要 忆阻器可以模拟生物突触行为而实现低功耗、并行计算、集成度高的神经形态计算, 因此已经引起广泛关注. 本文报道了一种基于溶液法制备的铯铅溴(CsPbBr₃)钙钛矿忆阻器, 以包裹在聚乙烯吡咯烷酮(PVP)中的CsPbBr₃为功能层的忆阻器表现出优异的空气稳定性, 同时成功模拟了生物突触行为, 包括突触可塑性(synaptic plasticity)、长时程增强(long-term potentiation, LTP)和短时程增强(short-term potentiation, STP)、幅度依赖可塑性、双脉冲易化(paired-pulse facilitation, PPF)、短期记忆和长期记忆以及两者的转变. 本研究展示的制备简单、成本低、稳定性好的钙钛矿人工突触, 为未来神经形态计算的应用提供了新的可能性.

关键词 铯铅溴, 钙钛矿, 忆阻器, 神经形态计算, 人工突触

在过去的十几年里, 数据量的激增使得人工神经网络越来越受到人们的关注, 并且应用于多个领域, 例如图像与自然语言处理、自动驾驶、金融和生物信息处理等^[1]. 目前的人工神经网络是利用传统计算机体系通过软件算法来实现的, 其能耗高且效率较低^[2,3]. 基于冯·诺依曼架构的传统计算机体系的特点是存储单元与计算单元分离, 在两者间的数据交换过程中消耗大量能源, 同时速度的提升也遭遇瓶颈^[4]. 由于计算单元的运算速度远比存储单元的读写速度快, 在两者的数据交换过程中计算单元必须消耗额外的时间等待存储单元完成读写, 由此带来的速度限制称之为冯·诺依曼瓶颈^[5]. 而人脑通过神经元和突触可以实现计算和存储同步进行, 有着可并行计算、功耗小、计算力大等特点^[6]. 因此, 模拟生物突触来实现神经形态计算是打破冯·诺依曼瓶颈的可行方案^[7,8]. 在生物大脑中, 学习与记忆行为与突触可塑性有直接的关系, 突触间的连接强度受到神经元活动的影响而得到增强或抑制^[9].

忆阻器是一种非线性电阻, 该元器件是1971年Chua^[10]从电路理论完备性角度出发预测出电阻、电容、电感之外的第4种无源基本电路元件, 其阻值能够随输入电流或电压的历史而发生变化, 这与突触可塑性相似, 因此忆阻器被广泛认为是模拟生物突触实现神经形态计算的理想器件^[11].

近十多年来, 基于忆阻器的人工突触已有广泛报道, 所用的阻变材料主要有金属氧化物^[12]和硫化物^[13,14], 这类无机物的制备需要经过复杂的工艺流程, 制备成本较高. 金属卤素钙钛矿因其可溶液制备、成本低廉、可大面积制备且具有优秀电学特性, 如电子捕获行为、光传输域大、电阻率高、反铁磁性、压电性、可光致发光、宽温度范围的阴离子电导率等, 广泛应用在光电器件研究中^[15~18]. 基于以上优点, 金属卤素钙钛矿也是作为阻变层来制备人工突触极具竞争力的材料^[19]. 目前, 以金属卤素钙钛矿作为阻变材料来制备忆阻器也有所报道. Gong等人^[20]使用CsPbBr₃量子点

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成功制备出拥有模拟型忆阻特性的三端口忆阻器。但由于该横向结构器件的沟道长度过长以及界面效应使得器件需要40 V以上的高操作电压,同时量子点的制备和复杂的器件结构也需要复杂的工艺而增加了制备成本,其突触可塑性也不够明显。John等人^[21]使用有机-无机杂化卤素钙钛矿制备出5层结构的人工突触,由于有机-无机杂化卤素钙钛矿对环境敏感,该器件依然面临稳定性的挑战。Wu等人^[22]通过添加ZnO来提高铯铅溴(CsPbBr₃)忆阻器的稳定性,但未能模拟出生物突触功能,只应用在存储领域中。因此,目前的卤素钙钛矿人工突触器件依然存在突触可塑性和稳定性不足的问题。鉴于金属卤素钙钛矿的优异特性和神经形态计算的迫切需求,有必要进一步探索制备出成本低廉、制备工艺简易、稳定性好且性能高的人工突触器件。

本文报道了一种基于溶液法制备的氧化铟锡(indium tin oxide, ITO)/CsPbBr₃:聚乙烯吡咯烷酮(PVP)/Au忆阻器。阻变层使用CsPbBr₃前驱体和PVP混合溶液旋涂在ITO玻璃上,通过高温退火生长出CsPbBr₃晶体,晶体被PVP包裹而隔绝大气避免被氧化,从而得到稳定性高的忆阻器件。ITO/CsPbBr₃:PVP/Au忆阻器表现出稳定且重复性高的阻变特性;同时该器件实现了生物突触功能的模拟,包括突触可塑性(synaptic plasticity)、长时程增强(long-term potentiation, LTP)和短时程增强(short-term potentiation, STP)、幅度依赖可塑性、双脉冲易化(paired-pulse facilitation, PPF)、短期记忆和长期记忆以及两者的转变。得益于良好的稳定性和突触功能模拟,ITO/CsPbBr₃:PVP/Au忆阻器有望在神经形态计算领域得以应用,打破传统计算体系的瓶颈。

1 实验

实验中使用的溶液为CsPbBr₃、PVP混合溶液(CsPbBr₃:PVP),将CsBr和PbBr₂以1:1的摩尔比溶于二甲基亚砜(dimethyl sulfoxide, DMSO)中,浓度为0.1 mol/L,并添加50 mg/mL的PVP,剧烈搅拌至完全溶解。所用基片使用清洗液、去离子水、乙醇、丙酮依次在超声机和清洗机中各清洗15 min。器件制备在氮气环境中进行,器件制备流程:首先在刻蚀有图案化ITO的玻璃基板上滴加混合溶液;然后以2000 r/min的速度旋涂60 s,随后放置于加热台上以250°C的温度退火15 min;最后使用掩膜板盖住器件,蒸镀约65 nm厚的图形化电极Au。器件结构示意图如图1(a)所示。

器件的电学测试在大气环境中进行,温度为300 K,

测试设备为Keithley 4200-SCS。在测试过程中,对下电极(ITO)电气接地,电压信号施加在上电极Au上;使用源-测量单元(source-measure unit)进行测试,该模块可以同时为器件施加电压信号并测量器件的响应电流。

2 结果与讨论

2.1 忆阻器阻变层形貌表征

器件的扫描电子显微镜(SEM)截面如图1(b)所示,可以看到CsPbBr₃纳米晶粒位于上下电极之间,晶粒间的空隙被PVP填充;PVP隔断了上下电极的直接接触,避免器件短路,同时包裹CsPbBr₃晶粒以隔绝CsPbBr₃晶粒与大气环境直接接触,避免被氧化。CsPbBr₃:PVP层表面形貌如图1(c)所示,右图为未经过退火处理的膜层形貌,左图的膜层分别经过250和300°C退火处理15 min。从图中可以看出,没有经过退火处理所形成的CsPbBr₃晶粒尺寸较小,晶粒间隙中存在未完全结晶的颗粒;而经过250和300°C退火后的器件形成大颗粒、结晶度高的膜层。X射线衍射(XRD)结果(图1(d))进一步显示了该现象,经过250°C退火的钙钛矿层在15.25°、21.71°、30.78°的衍射峰明显,分别对应(001)、(110)、(002)晶面;而未经过退火处理的钙钛矿层由于结晶度较弱,衍射峰不明显,只检测到1个(110)晶面(ICDD PDF#00-018-0364)。因此,经过250°C退火的CsPbBr₃:PVP膜层可以得到晶粒较大、结晶度高的CsPbBr₃晶体。

为了探究阻变层的元素分布,对经过250°C退火的CsPbBr₃:PVP膜层进一步表征,在15 kV的电压下获得的能谱仪(EDS)分析结果如图2所示。从图中可以发现,Cs、Pb、Br三种元素聚集在晶体所在区域,其中Br的含量最高,集聚性最明显;3种元素的摩尔比为Cs(L):Pb(M):Br(L) = 17.28:21.55:61.17,约1:1:3,符合CsPbBr₃的原子比。以上结果说明CsBr、PbBr₂、PVP混合溶液在经过退火处理后,CsBr与PbBr₂结合生成CsPbBr₃钙钛矿纳米晶体。

2.2 忆阻器的阻变特性与突触行为模拟

ITO/CsPbBr₃:PVP/Au器件的电流-电压(*I-V*)特性如图3所示。在器件电极上施加0→2→0 V、以0.02 V为步进的递增电压,之后施加0→2→0 V的反向递增电压。图3(a)为纵轴取对数处理的*I-V*曲线,退火后器件的*I-V*曲线展现出良好的滞回行为。在初次扫描时,0→1.3 V

图1 (网络版彩色)器件结构与表征结果。(a) Glass/ITO/CsPbBr₃:PVP/Au忆阻器的结构示意图, 右上角为CsPbBr₃晶体的结构图; (b) glass/ITO/CsPbBr₃:PVP/Au忆阻器的截面图; (c) 经过250°C退火(左下)、300°C退火(左上)和未经退火(右)的CsPbBr₃:PVP层SEM形貌图; (d) CsPbBr₃:PVP膜层的XRD测试结果, 上、中、下曲线分别代表250°C退火、未退火的ITO/CsPbBr₃:PVP器件和纯ITO层的测试结果

Figure 1 (Color online) Structure and characterization results of the device. (a) Glass/ITO/CsPbBr₃:PVP/Au memristor structure diagram. The upper right corner is the structure of CsPbBr₃ crystal. (b) SEM image cross-sectional view of glass/ITO/CsPbBr₃:PVP/Au memristor. (c) SEM topography of CsPbBr₃:PVP layer annealed at 250°C (top left), 300°C (bottom left) and unannealed (right). (d) XRD results of CsPbBr₃:PVP film, in which the ITO/CsPbBr₃:PVP device of 250°C annealed and unannealed, and pure ITO layer shown in up, middle, and down line, respectively

图2 (网络版彩色)250°C退火处理的CsPbBr₃:PVP膜层的EDS测试结果。(a)膜层表面SEM图; Cs(b)、Pb(c)和Br(d)元素在(a)所示区域的含量分布图

Figure 2 (Color online) EDS test of CsPbBr₃:PVP film annealed at 250°C. (a) SEM image of film surface. The content distribution of Cs (b), Pb (c) and Br (d) in the area shown in (a)

过程中为高阻态(high resistance state, HRS), 在1.3→2 V过程中逐渐向低阻态(low resistance state,

LRS)转变, 实现SET操作; 并且在2→0和0→-2 V过程中保持HRS。随后在-2→0 V过程中逐渐向LRS转变, 实现RESET操作。对器件施加多次扫描循环, 如图1(b)所示, 随着扫描次数的增加, 正电压扫描时, 电流滞回曲线逐渐上移, 表现出电导逐渐增大的情况; 而在反向电压扫描时, 滞回曲线向电流变小的方向移动, 表明器件电导逐渐减小。多次*I-V*扫描曲线说明ITO/CsPbBr₃:PVP/Au器件具有忆阻特性, 即电导随流经器件的电流变化而变化^[23]。制备完成的器件暴露在大气环境(10⁵ Pa, 300 K)9 d后, 对器件进行相同的*I-V*测试, 结果显示依然保持良好的忆阻特性(图3(c)), 说明高温退火形成的钙钛矿晶体在PVP包裹下对大气环境有着良好的稳定性, 为忆阻器的实际应用提供了良好的稳定性条件。相同的制备条件下, 只添加PVP的ITO/PVP/Au器件在电学测试中没有展现出滞回行为(图3(d)), *I-V*曲线呈线性, 说明该条件下的忆阻特性由CsPbBr₃晶体贡献。而对于在相同条件下制备的ITO/CsPbBr₃/Au器件(图3(e)), *I-V*曲线呈直线, 且在1.8 V时电流达到预设的限制电流(100 mA)。其原因可能是在未添加PVP的情况下

图 3 (网络版彩色)器件的 I - V 曲线。(a) ITO/CsPbBr₃:PVP/Au器件纵轴取对数的 I - V 曲线。(b) ITO/CsPbBr₃:PVP/Au器件正负电压重复扫描的 I - V 曲线。插图为负电压扫描部分放大图。(c) ITO/CsPbBr₃:PVP/Au器件暴露于大气中(温度约300 K)9 d后的 I - V 曲线。ITO/PVP/Au(d)和ITO/CsPbBr₃/Au(e)器件的 I - V 曲线。不退火(f)、200°C退火(g)和300°C退火(h)处理后ITO/CsPbBr₃:PVP/Au器件的 I - V 曲线

Figure 3 (Color online) I - V curves of the device. (a) The logarithmic I - V curve of the vertical axis of ITO/CsPbBr₃:PVP/Au device. (b) I - V curves repeated scanning with positive and negative voltages of ITO/CsPbBr₃:PVP/Au device. The inset is an enlarged view of the negative voltage scanning part. (c) I - V curves of ITO/CsPbBr₃:PVP/Au devices after 9 d of exposure to the atmosphere at a temperature of about 300 K. I - V curves of ITO/PVP/Au (d) and ITO/CsPbBr₃/Au devices (e). The I - V curves of ITO/CsPbBr₃:PVP/Au device after unannealed (f), annealed at 200°C (g) and annealed at 300°C (h)

CsPbBr₃晶体间的空隙过大, 导致上电极蒸镀时Au微粒通过空隙与下电极直接接触造成器件短路。对于没有经过退火处理的器件, 并没有表现出明显的滞回窗口(图3(f)); 相比于250°C退火处理, 在200和300°C退火处理后的器件则滞回行为表现更弱, 多次循环扫描的电流变化也更小(图3(g)、(h)), 即器件阻值变化幅度相对更小。推测阻变层中的CsPbBr₃结晶状态受到退火温度影响, 过低或过高温下所形成的CsPbBr₃晶体阻变层导致较差的忆阻特性, 因此下文中所用器件均在250°C退火条件下制备。

在人脑中, 学习与记忆行为与神经元之间的突触可塑性有关^[24]。图4(a)给出了神经元和突触的示意图, 突触前膜传输过来的信号可以使突触后膜产生兴奋性后突触电流(excitatory post-synaptic currents, EPSCs)或抑制性后突触电流(inhibitory post-synaptic currents, IPSCs)。神经元之间的连接强度(又称为突触权重)受到刺激信号的控制, 突触权重通过神经元活动得以增强(potential)或抑制(depression)^[25]。为了模拟突触可塑性, 对ITO/CsPbBr₃:PVP/Au器件上电极施加50个的连续尖峰脉冲(2 V, 50 ms), 每个脉冲后以低电压尖峰脉冲(0.3 V, 50 ms)来实时读取该时刻的电导值, 随后施加同数量的反向连续尖峰脉冲(图4(b))。测试结果如图4(c)所示, 在正向连续尖峰脉冲刺激下, 器件电导逐渐增大, 对应生物学中突触权重增强的过程; 而在反向连

续脉冲刺激下, 器件电导则逐渐减小, 对应突触权重的抑制过程。该结果表明ITO/CsPbBr₃:PVP/Au忆阻器成功模拟了突触可塑性^[26]。

为进一步测试器件突触可塑性模拟的可重复性, 如图5(a)所示, 在各50个正/反方向连续尖峰脉冲(+/-3 V, 50 ms)的交替刺激下(图5(a)上图), 器件响应电流(图5(a)下图)实现了周期性的增大和减小, 每个循环扫描中均可实现HRS与LRS的转换操作, 说明在ITO/CsPbBr₃:PVP/Au忆阻器中突触权重增强和抑制的过程有较高的可重复性; 并且在同一周期内经多次脉冲刺激后电流变化逐渐变小, 在负脉冲刺激下电导在刺激周期内达到饱和, 正脉冲刺激下电导增加量逐渐减小。该结果表明器件很好地模拟了生物突触中的长时程增强作用(long-term potentiation, LTP)和长时程抑制作用(long-term depression, LTD)^[27]。图5(b)显示了对器件进行HRS与LRS切换的可重复性测试结果, 施加交流矩形脉冲(幅度为2 V, 周期约4 s)到器件上, 长周期脉冲可保证器件在每个半周期内实现电阻切换, 并以0.1/-0.1 V的电压读取电导状态。结果表明在250个周期循环下, 器件依旧可以维持HRS和LRS的切换操作。图5(c)给出了图5(b)中的电导状态分布统计图, 可以明显区分HRS和LRS两种状态下的电导大小, 且分布集中。经统计, HRS的电导平均值 $\mu_H = 1.12$ mS, 标准差 $\sigma_H = 0.10$ mS; LRS的电导平均值 $\mu_L = 3.07$ mS, 标准差 $\sigma_L = 0.19$ mS。器

图4 (网络版彩色)突触可塑性模拟。(a) 神经元和突触示意图; (b) 模拟突触可塑性刺激信号的尖峰脉冲, 刺激信号幅度为2 V, 读取电导状态的电压为0.3 V; (c) 脉冲刺激下电导的增强和抑制

Figure 4 (Color online) Synaptic plastic simulation. (a) Schematics of neurons and synapse; (b) spike pulses of synaptic plastic stimulation with an amplitude of 2 V, and a voltage of 0.3 V for reading conductivity; (c) increase and suppression of conductivity under pulse stimulation

件的HRS中电导分布比LRS更为集中。由此可见, ITO/CsPbBr₃:PVP/Au忆阻器在电阻切换中具有优异的可重复性, 有利于在神经网络计算中的应用。

在生物学上, 记忆是突触的基本功能, 分为短期记忆和长期记忆, 与STP和LTP有关^[28]。其中, STP是突触权重的暂时性调节, 神经元刺激信号结束后突触权重在短期内可恢复到初始状态, 与大脑中模式识别等功能相关^[29-31]。其中PPF是STP的重要功能, 指的是在两个时间间隔小的神经元刺激信号中, 第二个信号刺激后的突触权重比前一个信号的更大, 且时间间隔越小效果越明显^[32]。PPF指数是后一个脉冲的响应信号 I_t 与前一个脉冲响应信号 I_0 的比值, 即PPF指数= I_t/I_0 。在

ITO/CsPbBr₃:PVP/Au忆阻器中模拟PPF功能, 改变两个电脉冲(3 V, 100 ms)的时间间隔 Δt , 电导变化量的PPF结果如图6(a)所示, $\Delta t \approx 0.17$ s时PPF指数为228%; 而 $\Delta t \approx 2.67$ s时, PPF指数为133%。从图中可以看出, 随着 Δt 的增大PPF指数呈指数下降, 测试结果能较好地对应指数拟合曲线, 说明器件成功模拟了生物突触中的PPF行为^[33]。

根据Atkinson和Shiffrin^[34]提出的记忆多重存储模型(the multi-store model of memory), 短期记忆经过多次重复刺激可转变为长期记忆, 在突触中则表现为突触权重的非易失性。本研究使用不同数量的正向尖峰脉冲(2 V, 100 ms)施加到ITO/CsPbBr₃:PVP/Au忆阻器的上电极, 随后以0.1 V的读电压读取器件电导的变化情况。结果如图6(b)所示, 10个尖峰脉冲刺激后, 电导在200 s内降低到原来的20%以下; 脉冲数量增加到70个以上时, 经过180 s, 电导仍保持在60%以上; 继续增大脉冲数量, 电导的非易失性则继续提升, 但提升效果变弱。上述结果表明本忆阻器可以实现短期记忆向长期记忆的转变^[33]。

除脉冲时序因素外, 刺激的强度也会影响突触权重的改变。如图6(c)所示, 对ITO/CsPbBr₃:PVP/Au忆阻器施加不同大小电压的正向尖峰脉冲, 随着电压的增加, 器件响应电流增大; 且在1 V脉冲下, 电流在10 s内便达到饱和值, 不再继续增加。而在2 V脉冲下, 25 s后才趋近饱和; 3 V时, 35 s内尚未观察到饱和现象。我们推测继续使用脉冲刺激, 器件的响应电流将进一步增大。在施加反向尖峰脉冲时, -3 V脉冲刺激下的器件电流迅速减小; -2 V脉冲刺激下则缓慢减小且变化幅度较小, 与图3(b)中的 I - V 曲线对应。而-1 V脉冲下的器件

图5 (网络版彩色)突触权重的增强与抑制测试。(a) 正负尖峰脉冲循环刺激下的电流响应(下图)。脉冲幅度为3 V, 脉宽为100 ms, 每50个尖峰脉冲电压方向转变1次(上图)。(b) 电阻变换的可重复性测试, 施加电压为周期约4 s、幅值为2 V的交流矩形脉冲(插图)。(c) 图(b)中的HRS和LRS的电导分布统计

Figure 5 (Color online) Tests of synaptic weight enhancement and inhibition. (a) Current response under cyclic stimulation of positive and negative spikes (below). The pulse amplitude is 3 V, the pulse width is 100 ms, and the pulse voltage direction changes once every 50 spikes (up). (b) The resistance-transformation repeatability test, applied to a rectangular AC pulse with a period of about 4 s and an amplitude of 2 V (inset). (c) The conductivity distribution of HRS and LRS under the test results from (b)

图 6 (网络版彩色)突触可塑性电学测试. (a) PPF行为模拟. 插图为脉冲示意图(3 V, 100 ms). (b) STP与LTP模拟, 分别在10、30、70和100个脉冲(2 V, 100 ms)刺激后, 使用0.1 V的读电压读取电导变化, 图中为归一化的电导变化. 幅度为1、2、3 V(c)和-1、-2、-3 V(d)的连续尖峰脉冲刺激下的电导响应, 读电压为0.1 V

Figure 6 (Color online) Electrical tests of synaptic plasticity. (a) PPF behavior simulation. The inset is a pulse diagram (3 V, 100 ms). (b) STP and LTP simulation. After 10, 30, 70 and 100 pulses (2 V, 100 ms) stimulation, respectively, the conductivity changes were read with a read voltage of 0.1 V. The conductivity curves have been normalized. Conductance response to continuous peak pulses of 1, 2, 3 V (c) and -1, -2, -3 V (d). The read voltage is 0.1 V

电流无明显变化, 说明该幅值下的负脉冲信号对器件电导无调节作用. 正负脉冲下的非对称电流响应与器件上下电极材料的差异以及电极与阻变层的界面不一致有关. 刺激脉冲电压幅值越大, ITO/CsPbBr₃:PVP/Au忆阻器的响应电流越大, 实现生物突触的脉冲幅值依赖可塑性(spike-amplitude dependent plasticity, SADP)模拟^[14].

3 结论

本研究利用溶液法制备了结构为ITO/CsPbBr₃:PVP/Au的钙钛矿忆阻器. 通过高温退火生长CsPbBr₃纳

米晶体, 包裹在CsPbBr₃外的PVP隔绝了大气环境, 避免易氧化的CsPbBr₃与空气直接接触, 从而使忆阻器能在空气中长期存放, 并依然保持良好的忆阻特性. 在模拟突触行为的测试中, ITO/CsPbBr₃:PVP/Au忆阻器表现出优异的操作重复性, 并实现了生物突触功能的模拟, 包括突触可塑性、LTP和STP、SATP、PPF、短期记忆和长期记忆以及两者的转变. 得益于良好的稳定性和突触功能的模拟, ITO/CsPbBr₃:PVP/Au忆阻器有望应用于神经形态计算领域, 为打破传统计算体系的瓶颈、提升计算速度、促进新一代计算机体系的建立提供了新的可能性.

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Summary for “用于神经形态计算的CsPbBr₃钙钛矿忆阻器性能研究”

Properties of memristor based on CsPbBr₃ perovskite for neuromorphic computing

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In the past few decades, the application of electronics and computers has dramatically changed the way that we learn, work, and live. Advances in semiconductor technology have enabled computers to perform increasingly well. The reduction in chip size has led to lower preparation costs, faster computer computing rates, and less power consumption. More than 50 years have passed since the development of Moore's law, and the characteristic length of silicon-based transistors is getting closer to the physical limit. On the other hand, conventional computer systems based on the von Neumann Architecture have additional latency and power consumption due to the separation of the computation and storage centers, leading to the emergence of the von Neumann Bottleneck, which limits the further improvement of the computational speed. In this background, neuromorphic computing inspired by the human brain has attracted a lot of attention in recent years. This integrated computation and storage center architecture can provide highly parallel, fast, efficient, and low-energy computing and storage to overcome the von Neumann bottleneck.

Unlike the current mainstream neuromorphic computing that relies on software algorithms, memristors can mimic the synaptic function of biological nerves and thus build electronic devices that implement neuromorphic computing at the physical level. Nowadays, computer systems on silicon-based chip have great limitations and face new challenges for further development. The memristor-based neuromorphic computing system provides an alternative way to realize the integration of memory and computation, bio-inspired parallel computing and efficient reconfigurable memory computer system under the development needs of big data and internet of everything. To date, several materials have been applied to the development of memristors, such as oxides, two-dimensional materials, organic materials. However, these materials have certain limitations, such as complicated preparation processes, poor stability and reliability, and insufficient bionic properties. While perovskites have excellent electronic properties, which is widely used in light-emitting diodes, solar cells, and other fields. Perovskites are suitable for the preparation of memristive devices because of the advantages of high defect tolerance, high carrier mobility, and electron capture behavior. In recent years, perovskite-based artificial synapses have also been gradually developed, but they still have the problems of lack of stability and performance.

Herein, we reported a highly stable memristor prepared with cesium lead bromide (CsPbBr₃) perovskite and polyvinylpyrrolidone (PVP) by a one-step method with the structure of ITO/CsPbBr₃:PVP/Au. We used CsPbBr₃ perovskite as the resistive switching layer material and added PVP to the precursor solution to prepare memristors that can be used for neuromorphic computing. After different annealing temperatures, CsPbBr₃ crystals with different sizes were formed, and the device annealed at 250°C had the most excellent performance. The ITO/CsPbBr₃:PVP/Au memristor device still maintains excellent performance when exposed to air for 9 d, exhibiting excellent stability. Meanwhile, our device successfully simulates biological synaptic behavior, including synaptic plasticity, long-term potentiation (LTP) and short-term potentiation (STP), amplitude-dependent plasticity, paired-pulse facilitation (PPF), short-term and long-term memory. The excellent performance means that our devices can be widely used in neuromorphic computing systems, which is a step forward for the development of next-generation computer systems.

CsPbBr₃, perovskite, memristor, neuromorphic computation, artificial synapse

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