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A Mechanism Underlying the Electrical Polarity Detection of Sensitive Plant, *Mimosa Pudica*

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P A P E R   I N F O

A B S T R A C T

Natural indicators of the electrical polarity of a direct current (DC) source is limited to semiconductor based diodes and transistors. Recently a novel bio-natural indicator of the polarity of a DC source have been reported. *Mimosa Pudica* or sensitive plant is found to be a natural detector of a DC source polarity, however the mechanism underlying this phenomenon is not known. This paper aims to develop a physical and engineering based model to explain the mechanism of this phenomenon. This model suggests that spatial placement of ion release sites along the pathway of electric signal is crucial to obtain polarity effects. A combination of this spatial placement of ion release sites and a delay in the opening of K^+ ion channel with respect to Cl^- ion channel can explain this one-way switch behavior.

1. INTRODUCTION

In every closed electrical circuit with an electric power source like a battery, electrons flow from the negative pole to the positive pole. Detecting the real direction of electron flow is important for many scientists from introductory physics teachers and textbook writers to professional electrical engineers [1]. Especially, it is crucial for solid-state physicists who are concerned with the actual motion of electrons in substances. In practice, there are very limited methods of recognizing the polarity of a DC electric source. Voltmeters and oscilloscopes which are usually being used to recognize the polarity of a DC power source work based on a convention [2, 3]. The only known natural sensitive devices to the electrical polarity are semiconductor based light-emitting diodes (LED) and transistors. Finding a simple and straightforward method to detect the polarity of an electric source (the true electron flow direction) is still important and has a broad range of applications.

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In the other hand, in nature, all higher level plants utilize electrical signal to regulate physiological functions [4]. Signals, similar to action potentials (APs) in nerves, have been observed in sensitive plants like *Mimosa pudica*. Electrical signals in *Mimosa Pudica* are generated by various stimulations like knocking, touching, cutting, burning, chemicals and electric shocks. These stimuli trigger rapid leaf movements in sensitive plants and cause the petiole to hang down [5-9]. Even the reaction of internal cells in this plant has been investigated [10].

In animals, APs are electrical messages that propagate rapidly along axons, the surface of certain muscles and glandular cells. They have a short duration of only a few milliseconds, and move with constant velocity while maintaining a constant amplitude [11]. APs are produced by voltage-gated ion channels, which open in an all-or-none fashion when the membrane potential exceeds a certain threshold. The opening of Na^+ channels causes a rapid depolarization of the membrane, generated by an inward flow of Na^+ ions, followed by a repolarization phase mediated by outward-flowing K^+ ions, which permeate through voltage gated K^+ channels. However, in plant cells, APs

depend on Ca^{2+}, Cl^-, and K^+ ions. Instead of an inward flow of Na^+ during the depolarization phase, an outward flow of Cl^- ions is observed [4]. The Ca^{2+} is assumed to play an important role in this process, since voltage-gated anion channels require the elevated cytoplasmic levels. Electrical signals in plants travel along plasmodesmata from one cell to another, or, for long-range transmission, along the phloem, which extends continuously through the plant. Sieve elements are considered low-resistance pathways for AP transmission [4, 12]. In our previous study, we have reported an interesting discovery by investigating the response of *Mimosa pudica* to the electrical stimulation of its petioles [9]. As Figure 1 shows, the negative pole of a battery was connected to a petiole on the right hand side and the positive pole was connected to another petiole on the left hand side of the plant (Figure 1a).

A few seconds (about 3 seconds) after closing the switch, the negative side petiole hanged down from its junction point to the stem (Figure 1b). Waiting about 30 minutes will let the bent branch to return completely to its normal position. Then, we changed the polarity of the battery (connecting the positive pole to the right

hand side petiole and the negative pole to the one on the left, Figure 1c). Again the petiole connected to the negative pole of the battery (the left side branch) hanged down after a few seconds (Figure 1d).

Based on our experimental results and observations, here, a model based on spatial placement of ion release sites along the pathway is proposed which explains our experimental results.

2. MODEL

In this model, we assume that the transmission pathway of the plant can be in two different states, a non-conducting and a conducting state (Figure 2). In the non-conducting state, anion channels which are embedded into the plasma membrane are in an inactive and closed state. Charge carriers are bound into a stable resting configuration through active processes, resulting in an excess of negative charges on the intracellular side, and positive charges on the extracellular side along the plasma membrane (Figure 2, upper panel).
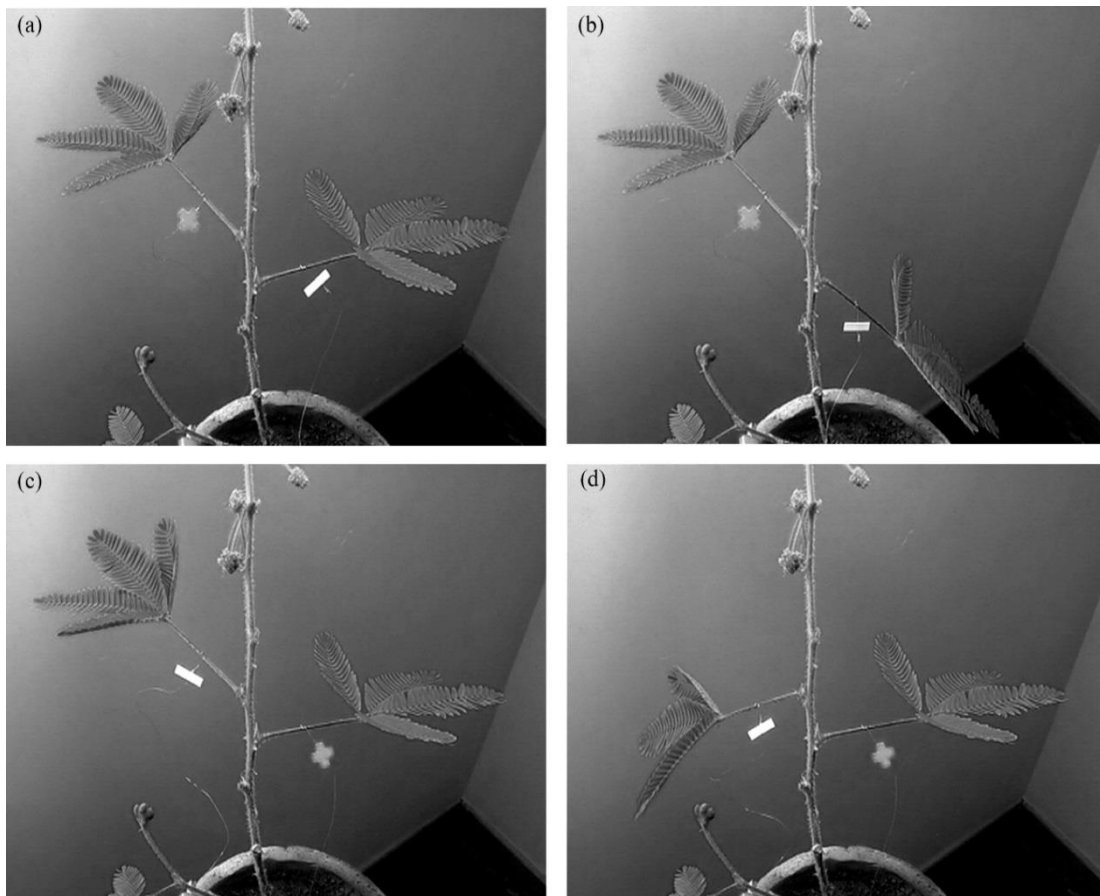

Figure 1. Electrical stimulation and behavior of the petioles of *Mimosa pudica*. (a, b) Behavior of the petiole of the sensitive plant before (a) and after (b) the stimulation, while the negative pole of the battery is connected to the right hand side petiole. (c, d) The negative pole of the battery is connected to the left hand side petiole
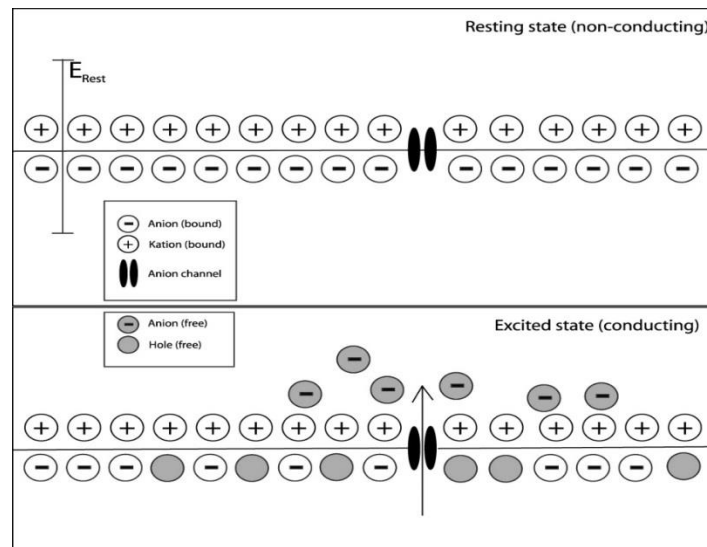
Figure 2. Conductive states in plants. Upper panel: In the non-conductive state of the plant transmission pathway, anion channels are closed and ions are bound into a resting configuration. Lower panel: In the conductive state, i.e., during an AP, the anion channel is open and anions are freed and released to the extracellular side, leaving holes behind, representing a lack of negative charges. Anions and holes are free charge carriers in the conductive state and are the basis for AP transmission.

In the conducting state, anion channels are open, e.g., as a response to an electrical signal, and anions at the intracellular side are pulled away and released to the extracellular side. This will leave intracellular side with a lack of negative charges, which are synonymous with holes in semi-conductor physics, as compared to the resting configuration, behind. The released anions and corresponding holes represent free charge carriers of the system. Hence, the transmission of an AP is equivalent to movement of charge in the conducting state. Polarity observed in *Mimosa pudica*, allowing electrical current or signals to propagate only in one direction (usually from the leaf to the stem but not in the opposite direction), indicates the existence of a rectifying mechanism in the plant's substrate for ionic signal transmission.

A schematic of the model is given in Figure 3. Along the signal transduction pathway of the plant, APs are generated and travel from oneexcitable area, containing voltage-gated Cl^- and K^+ channels, to the next with velocity v. During this phase of passive transmission, the signal will suffer somedegradation. We further assume that the flow of passive transmission is determined by the outward potential, i.e., following the convention, from the positive to the negative pole. The arriving electrical signal at an un-activated excitable area causes a depolarization of the membrane potential in the area, which leads to the opening of voltage-gated ion channels. The K^+ ion channel, responsible for re-polarization, opens with a delay Δt with respect to the Cl^- channel. Such a delay is commonly observed in animal K^+ channels and determines (among other factors) the characteristic

shape of APs [13]. Spatial placement of ion release sites along the pathway is crucial to obtain polarity effects. We assume that an external potential is placed along the pathway. The poles are symbolized as − and + symbols in Figure 3. We assume that Ca^{2+} stores are placed at closest distances Δs from the excitable area contained voltage gated ion channels. We first consider an electrical signal arriving from the right, moving from the + to the − pole (Figure 3, left panel). Note that electrical signals, i.e., which is peaks in the membrane potential, can move in both directions, because passive transmission can be mediated by either a lack of Cl^- ions (similar to hole-transmission in semiconductors) on the interior side of the membrane or by an excess of Cl^- ions on the exterior side of the membrane. The electrical signal causes the release of Ca^{2+} ions from the intracellular store before it reaches the excitable area. Ca^{2+} ions diffuse in the direction of the external field and interact with the Cl^- channels, which can thus open in response to the incoming electrical signal. If the electrical signal arrives from the other direction (Figure3, right panel) it also opens a Ca^{2+} store ontime (symmetry), but the Ca^{2+} ions will be pulled by the external field away from the excitable area and thus not reach Cl^- channel, which will thus fail to open inresponse to the electrical signal and no AP will be generated. The electrical signal will be diminished by the ion flow caused by the K^+ channel.

The model predicts that polarity will be diminished at high levels of intracellular Ca^{2+}, which could be tested experimentally. Furthermore, if no external field is applied, electrical signal can travel in both directions along the pathway.
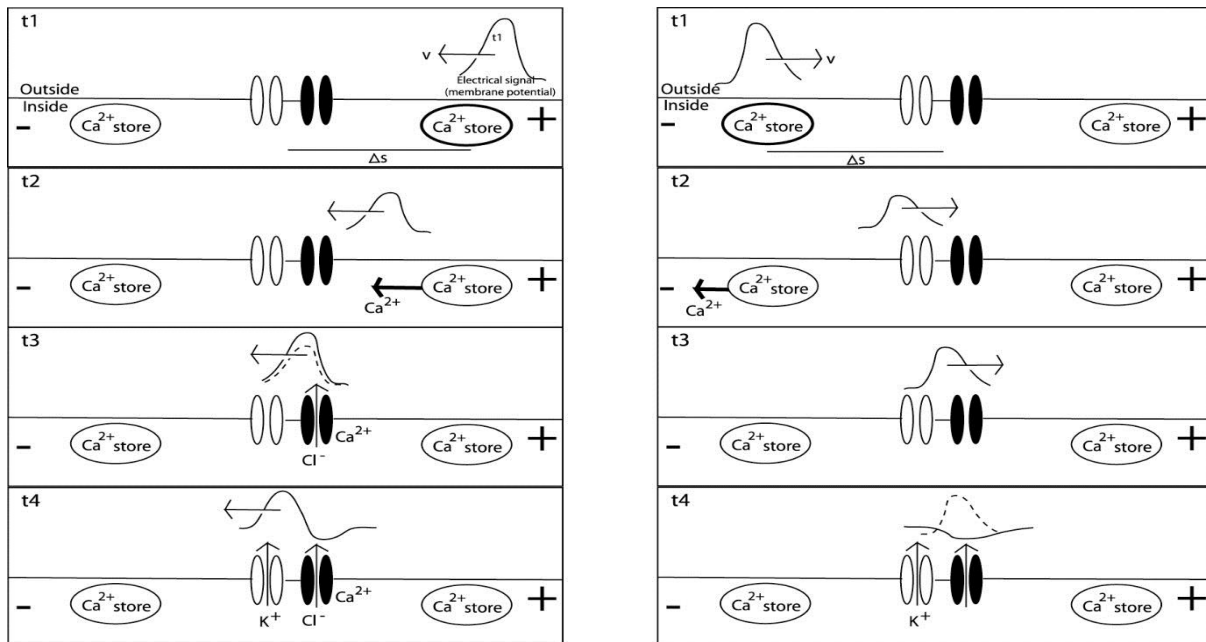
Figure 3. Schematic model of the polarity detection of *Mimosa pudica*. Left panel: An electrical signal travelling from the positive to the negative pole of an external field applied to the transmission pathway cause the release of Ca^{2+} ions, which are pulled towards the excitable area, where they interact with the Cl^- channel, which opens in response to the electrical signal. As a result, an AP is generated. Right panel: An electrical signal traveling in the opposite direction also causes the release of Ca^{2+} ions, but the Ca^{2+} ions are pulled away from the excitable area and the Cl^- channel fails to open in response to the arriving signal. No AP is generated. The electrical signal is diminished through the ionic currents caused by the K^+ channel.

3. DISCUSSION

Many studies have investigated the behavior of the sensitive plants in response to a stimulation of petiole and the plant pulvinus [4, 5, 14-16]. In the other hand, many scientists and engineers need to know the real electron flow direction in electrical circuits. However, in our previous study, we have stimulated two different petioles in opposite sides of the sensitive plant (*Mimosa Pudica*) and have shown that it can recognize the polarity of a DC source, e.g., a battery.

This model indicates that spatial placement of ion release sites along the pathway of Action Potential (AP) and a delay in the opening of K^+ ion channel with respect to the Cl^- channel are crucial to obtain polarity effects. The results about involving calcium channels in *Mimosa pudica* bending are similar to those obtained from different electrical stimulation [7, 16]. The model predicts that polarity will be diminished at high levels of intracellular Ca^{2+}, which could be tested experimentally.

4. ACKNOWLEDGEMENT

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چکیده

تشخیص‌دهنده‌های قطب‌های الکتریکی یک منبع جریان مستقیم فقط به دیودها و ترانزیسـتورهای بـر پایـه نیمه‌رسـاناها محدود می‌شوند. اخیرا یک نشانگر زیستی‌ـ‌طبیعی جدید قطب‌های الکتریکی یک منبع جریان مستقیم گزارش شده اسـت. مشخص شده است گیاه حساس (میموزا پودیکا) یک نشانگر طبیعی و زنده قطب‌هـای الکتریکـی اسـت، ولـی سـازوکار عملکرد آن مشخص نیست. این مقاله یک مدل فیزیکی‌ـ‌مهندسی را برای توضیح این پدیده ارائه می‌کند. این مدل پیشـنهاد می‌کند که محل فضایی سایت‌های آزادسازی یون در طول مسیر سیگنال الکتریکی جهت دسـت‌یـابی بـه اثـرات قطـبش ضروری است. ترکیبی از محل قرارگیری سایت‌های آزادسازی یون و یک تاخیر در بازشدن کانال یون پتاسیم نسـبت بـه کانال یون سدیم می‌تواند این رفتار سوئیچ یک طرفه را توضیح دهد.

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