Metrology

Nanowire device slips ahead in current race

Masaya Kataoka

A phenomenon known as quantum phase slip has been used to generate a current by moving pairs of electrons through an ultrathin wire. The feat is good news for efforts to pin down the standard unit of current. See p.45

The standard unit of electric current, the ampere, is one of the seven base units in the International System of Units. But measuring a current exactly in amperes is not an easy task. In fact, in 1990, attempts to pin down the ampere were abandoned in favour of using the volt (which measures voltage) and the ohm (which measures electrical resistance) as primary electrical units[1] (see go.nature.com/3umryol). On page 45, Shaikhaidarov *et al.*[2] now report a method for producing current in discrete, measurable steps by irradiating a wire that is a few thousand times thinner than a human hair. The approach could be used as a quantum current standard for the ampere – providing a missing piece in electrical metrology.

Although electrical conduction is a complex phenomenon, on a fundamental level, the transport of charged particles is governed by a surprisingly simple relationship involving the elementary charge (which is equal to the magnitude of the charge on an electron) and the duration or frequency of the process. In principle, this fact can be used to measure current accurately. Knowing exactly how many electrons are transferred through a system in a given amount of time can reveal precisely how much charge is transferred – in other words, how much electric current is produced.

The concept of basing a current standard on the transport of single electrons emerged around 30 years ago, with the dawn of nanoscale technologies[3,4]. This development was partly motivated by the difficulty in performing electromechanical experiments to generate a current measured in amperes, using the definition it had then, which was based on the force law proposed by the French physicist André-Marie Ampère. In 2019, a revision of four out of the seven base units included a redefinition of the ampere in terms of the fixed numerical value of the elementary charge (see go.nature.com/3umryol).

The most popular method for generating a primary reference current for the ampere on the basis of the new definition uses devices called single-electron pumps[5]. These pumps operate by periodically taking an electron from a source reservoir, depositing it in a small confined area, known as a quantum dot, and then releasing the electron into a drain reservoir, thereby completing the transfer of one electron in each cycle. The accuracy of this electron-transfer process has been improved over the past two decades, so that now a pump that completes one billion cycles will make fewer than 100 errors[6]. The general consensus[7] is that an accuracy of around ten errors per billion cycles is required if the pump is to be used as the primary ampere standard in metrological laboratories.

Although it is plausible that single-electron pumps can achieve such accuracy, it is difficult to verify this accuracy. The current produced by a single-electron pump is small. The operation frequency of the device is limited to around one gigahertz (1 GHz = 10^9 Hz), and this gives rise to a current on the order of 100 picoamperes (1 pA = 10^{-12} A). It takes several hours to take enough current measurements to average out noise in order to achieve fewer than 100 errors per billion cycles.

Obtaining the desired improvement in measurement uncertainty would require a measurement time 100 times longer than this – meaning several days for a single data point. This is too slow to be of practical use. However, because the measurement uncertainty is dominated by noise, the relative uncertainty that can be achieved is inversely proportional to the current level. Therefore, increasing the current to one nanoampere would allow a measurement resolution of ten errors per billion cycles to be achieved in several hours. In this regard, the device that Shaikhaidarov and colleagues used, known as a quantum phase-slip device, has a considerable advantage over single-electron pumps. The authors demonstrated that their device can be operated at a frequency of up to 26 GHz, producing a current of 8.3 nA.

The name of the device refers to the physical phenomenon that occurs when magnetic flux 'tunnels' across a superconducting nanowire – meaning its quantum-mechanical state hops across the wire[8]. This tunnelling event has a strange effect on a pair of electrons in the wire, known as a Cooper pair. The wave-like nature of Cooper pairs can be described by a phase, which is the point in the cycle of the wave at any given time. The magnetic-flux tunnelling has the effect of making this phase shift by one complete cycle – hence the term 'phase slip'. This phase slip is key, because it can be used to transfer Cooper pairs through the nanowire, taking with it a charge that is exactly twice the (negative) elementary charge (Fig. 1a).

This phenomenon is related to the Josephson

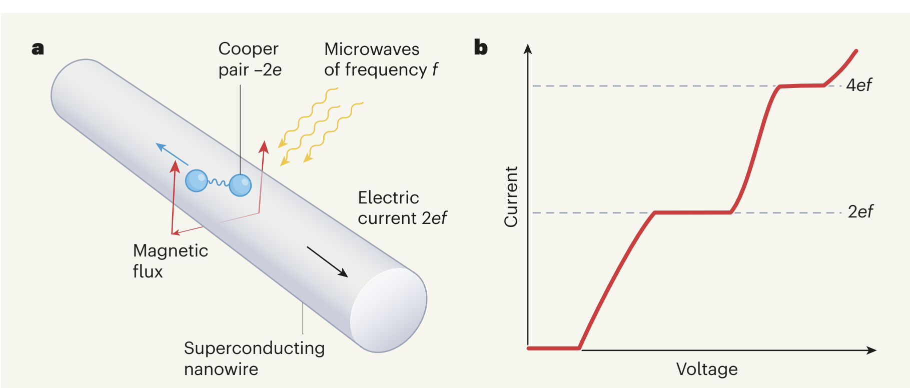

Figure 1 | An accurate method for measuring electric current. Shaikhaidarov *et al.*[2] used a tool known as a quantum phase-slip device to produce the electric current associated with the movement of pairs of electrons. **a**, Microwave radiation applied to a superconducting nanowire induces magnetic flux to 'tunnel' across the wire (yellow arrows), thereby transferring pairs of electrons known as Cooper pairs periodically with the same frequency (f) as the microwaves. Each electron has a charge of $-e$, where e is known as the elementary charge, and so the (positive) current that results from the charge transfer is equal to $2ef$. **b**, As the voltage across the wire increases, the current increases. When the wire is irradiated, the transfer of electron pairs creates steps in the current–voltage relationship at multiples of $2ef$. These steps could be used as a primary reference for the base unit of current, the ampere.

effect, in which the tunnelling of a Cooper pair across a gap between superconducting wires is associated with the transfer of magnetic flux through the gap. When a Josephson tunnelling device is irradiated by microwaves of a certain frequency, it produces a voltage step related to that frequency[9]. This is known as the a.c. Josephson effect, and is widely used as the basis for voltage metrology.

In the equivalent experiment using a quantum phase-slip device, microwaves applied to a superconducting nanowire drive the magnetic-flux tunnelling, periodically transferring Cooper pairs one by one with the same frequency as the microwaves. This process generates a quantized current equal to twice the elementary charge, multiplied by this frequency (Fig. 1b). And it can happen on a much faster timescale than that associated with electron transfer in single-electron pumps. Shaikhaidarov *et al.* observed current steps that were consistent with this quantization condition in the current–voltage characteristics of a niobium nitride wire. The wire had been embedded in a circuit that was carefully designed to protect it from external noise, and then cooled to 10 millikelvin.

Shaikhaidarov and co-workers' result is great news for metrologists. Instrument manufacturers and laboratories that calibrate measuring devices — as well as anyone tasked with measuring electric currents precisely — will benefit from the improved accuracy and sensitivity offered by this new approach. However, there is a caveat: the observed current steps are not completely flat with respect to the voltage applied to the device, so the accuracy of the quantized reference level is no more than 10% at present. The authors argue that improved noise filtering would allow the steps to be flat at a level of ten (or fewer) errors per billion cycles, as required for metrological applications. But the accuracy needs to be 10 million times better than that reported, which is a huge mountain to climb.

So the race is on: single-electron pumps or quantum phase-slip devices? Which would you bet on? As it turns out, there might be no need to choose. The guidelines for the International System of Units do not specify how the primary ampere standards should be built. Having multiple methods for primary standards has many advantages, such as providing ways to cross-check the results and covering a wide range of current magnitudes. These are benefits that the volt and ohm do not have at present. Measurements of the ampere might therefore one day become more accurate and more robust than those of the volt and ohm. On that day, the ampere will regain its pride of place as a base unit in the international system.

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1. Taylor, B. N. & Witt, T. J. *Metrologia* **26**, 47–62 (1989).
2. Shaikhaidarov, R. S. *et al. Nature* **608**, 45–49 (2022).
3. Kouwenhoven, L. P., Johnson, A. T., van der Vaart, N. C., Harmans, C. J. P. M. & Foxon, C. T. *Phys. Rev. Lett.* **67**, 1626–1629 (1991).
4. Pothier, H., Lafarge, P., Urbina, C., Esteve, D. & Devoret, M. H. *Europhys. Lett.* **17**, 249–254 (1992).
5. Kaestner, B. & Kashcheyevs, V. *Rep. Prog. Phys.* **78**, 103901 (2015).
6. Stein, F. *et al. Metrologia* **54**, S1–S8 (2017).
7. Keller, M. W. *Metrologia* **45**, 102–109 (2008).
8. Astafiev, O. V. *et al. Nature* **484**, 355–358 (2012).
9. Josephson, B. D. *Phys. Lett.* **1**, 251–253 (1962).

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Climate science

Risk management alone fails to limit hazard impact

Beth Tellman & Hallie Eakin

An analysis of floods or droughts that hit the same place twice shows that using risk management alone does not reduce the effect of extreme events. Addressing the social drivers of hazard impact, equitably, is essential. **See p.80**

Floods and droughts seem to be occurring with increasing frequency and severity, pushing the limits of society's ability to prepare for these extreme events through prediction and effective adaptation. We would like to believe that we learn from each disaster, and are thus better adapted to handle the next one. But is this really the case? On page 80, Kreibich *et al.*[1] examine 45 places where an extreme flood or drought happened twice, and determine whether risk-management strategies successfully reduced the impact of the second disaster. The authors' analysis suggests that adaptation is nearly always limited, and that the impact of a second event is not reduced by risk-management strategies when the event is more extreme than the first one.

Kreibich and her 91 co-authors from around the world documented 26 pairs of floods and 19 pairs of drought events occurring between 1947 and 2019 — with each pair having occurred in the same area. They compared the two events of each pair in the following ways: the severity of the hazard; the population's exposure (who or what were in harm's way) and vulnerability (the ability to cope with the disaster); the risk-management strategies in place (such as early-warning systems, reservoirs or levee construction); and the impact of the event (deaths and economic damage). Their extensive documentation and classification of each pair of events in terms of these factors has generated a valuable data set of the change in flood and drought impacts across time; this is now publicly available for further analysis. To ensure reliability, each event was classified by multiple scientists, including those familiar with the region in each case.

The authors' research shows that the impact of the second drought or flood was less than that of the first in 20 of the 45 cases. But in all but 2 of these 20 cases, the second hazard was no more severe than the first, and the vulnerability of the population had decreased. In the 13 cases in which the impact of the second event was higher than that of the first, 12 had an increase in exposure relative to the first event, despite showing reduced vulnerability and improvements in risk management in many cases. In the remaining 12 cases, the impact of the two events was the same.

The most alarming finding of the study is that the impact of the second drought or flood was larger than that of the first in all but two cases in which it was the more extreme event — no matter how much risk management had been undertaken, or to what extent exposure and vulnerability had been reduced. The results imply that investments in managing risk and curbing vulnerability following one severe event might not make a society sufficiently adaptive to reduce the risk from unprecedented subsequent events, which are increasing in a changing climate.

Exposure and vulnerability are inextricably linked[2]. It is well established that populations that are exposed to droughts and floods — often by necessity, as a last resort and through no choice of their own — are also especially vulnerable to these events[3] (Fig. 1). This means that investing in risk management alone, by improving flood early-warning systems, for example, won't substantially reduce flood fatalities and damage if people continue to settle in floodplains. Managing flood risk by constructing levees, or drought risk by expanding irrigation infrastructure, can also backfire, because these developments incentivize people to settle in floodplains or start new agricultural activities in drought-prone areas.

Kreibich *et al.* also found that, unlike in