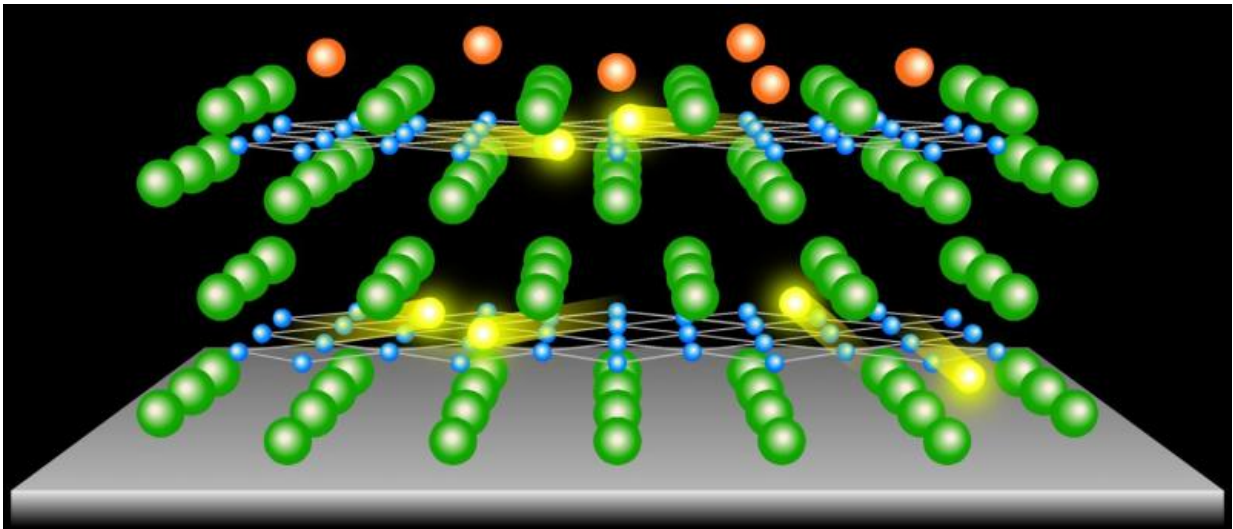


# High-temperature superconductivity in atomically thin films

June 2 2015

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Blue and green circles indicate iron (Fe) and selenium (Se) atoms, respectively. The superconducting transition temperature is tuned by introducing electrons by depositing potassium atoms (orange circles) on the surface. Yellow circles represent a pair of superconducting electrons (Cooper pair). Credit: Takashi Takahashi

A research group at Tohoku University has succeeded in fabricating an atomically thin, high-temperature superconductor film with a superconducting transition temperature ( $T_c$ ) of up to 60 K ( $-213^\circ\text{C}$ ). The team, led by Prof. Takashi Takahashi (WPI-AIMR) and Asst. Prof. Kosuke Nakayama (Dept. of Physics), also established the method to

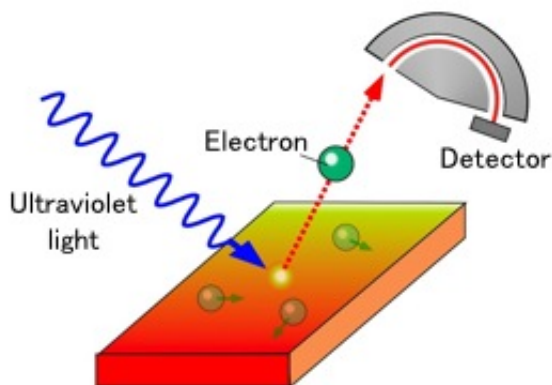
control/tune the  $T_c$ .

This finding not only provides an ideal platform for investigating the mechanism of [superconductivity](#) in the two-dimensional system, but also paves the way for the development of next-generation nano-scale superconducting devices.

The research results were published in *Nature Materials* on June 1, 2015.

Superconductors are regarded as one of the most promising candidates for next-generation advanced electronic devices, because the unique quantum effects in [superconductors](#) are a great advantage in achieving the energy-saving and ultrahigh-speed processing.

However, the device application of superconductors has long been hindered. The largest obstacle is the necessity of a huge and expensive cooling system with liquid helium, because of the low  $T_c$  of [conventional superconductors](#), which is close to absolute zero (0 K, - 273 °C). It has also been a big challenge to realize the high-density integration of superconductors into electronic devices. In order to overcome these problems, it is definitely necessary to develop a new superconductor with higher-  $T_c$ , that can be fabricated into a thin film.



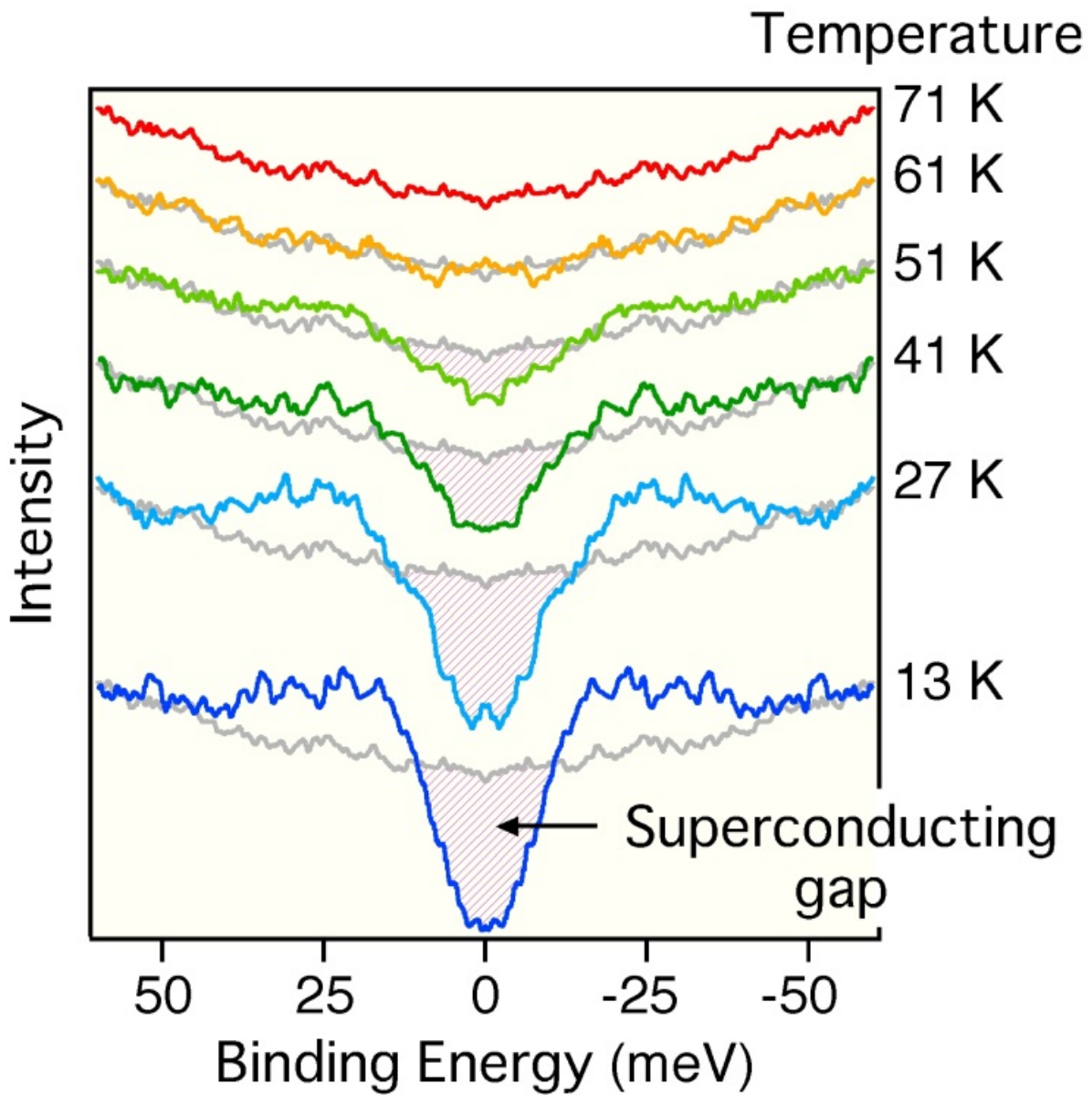
Electrons are emitted from the surface by shining ultraviolet light. The electronic structure of crystal is determined by measuring the energy and the emission angle of electrons. Credit: Takashi Takahashi

The research team at Tohoku University turned its attention to iron selenide (FeSe), which is a member of [iron-based superconductors](#). While the  $T_c$  of bulk FeSe is only 8 K (-265 °C), a signature of higher- $T_c$  superconductivity has been suggested in ultrathin film and its verification has been urgently required.

The researchers at first fabricated high-quality, atomically thin FeSe films [Fig. 1], with thickness of between one monolayer (which corresponds to three-atoms thickness) and twenty monolayers (sixty-atoms thickness), by using the molecular-beam-epitaxy (MBE) method. Then they carefully investigated the electronic structure of grown films by angle-resolved photoemission spectroscopy (ARPES) [Fig. 2].

In the ARPES measurement, the researchers observed the opening of a superconducting gap at low temperature, which is direct evidence of the emergence of superconductivity in the films. The researchers found that the  $T_c$  estimated from the gap-closing in a monolayer film is surprisingly high (above 60 K), which is about 8 times higher than the  $T_c$  of bulk FeSe.

While multilayer films do not show superconductivity in the as-grown state, the researchers have discovered a novel method to deposit alkali atoms onto the films and thereby control the electron density in the film. By employing this method, the researchers have succeeded in converting non-superconducting multilayer FeSe films into high- $T_c$  superconductors with  $T_c$  as high as ~50 K.



The superconducting gap (highlighted by shaded region) is clearly observed at low temperatures. With increasing temperature, the gap is gradually reduced and disappears at around 60 K. Credit: Takashi Takahashi

The present result gives a great impact to both the basic and applied

researches in superconductors. The researchers have clearly shown how the superconductivity is emerged, enhanced and controlled in atomically thin FeSe films. While the  $T_c$  achieved in this study (50-60 K) is still lower than that of the cuprate high- $T_c$  superconductors (highest  $T_c$ ?135 K) which caused the "high- $T_c$  fever" in the world 30 years ago, it obviously exceeds the record of other "high- $T_c$  superconductors" such as fullerene (C<sub>60</sub>) superconductors ( $T_c$ ~33 K) and MgB<sub>2</sub> ( $T_c$ ~39K), closely approaching the temperature of liquid nitrogen (77 K).

The present report would lead to intensive researches to further increase  $T_c$  by changing the number of atomic layers, the amount of doped electrons and the species of substrate. The present result would also widen the range of both basic and applied researches on superconductivity, because the  $T_c$  of 50-60 K achieved in the present study is high enough to keep the superconducting state by using a closed-cycle-gas-type cooling system without liquid helium.

The present success in fabricating an atomically thin high-temperature superconductor not only provides an ideal platform to investigate the novel two-dimensional superconductivity, but also opens a route to developing an ultimate superconducting nano-device consisting of atomic-size electronic parts. The ultrathin high- $T_c$  superconductor would effectively contribute to the significant down-sizing and consequent high-density integration in electric circuits, leading to the realization of future-generation [electronic devices](#) with high energy-saving and ultrahigh-speed operation.

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**More information:** "High-temperature Superconductivity in Potassium-coated Multilayer FeSe Thin Films" *Nature Materials*, 2015.

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