Non-reciprocal acoustoelectric amplifiers for very high frequency sound waves

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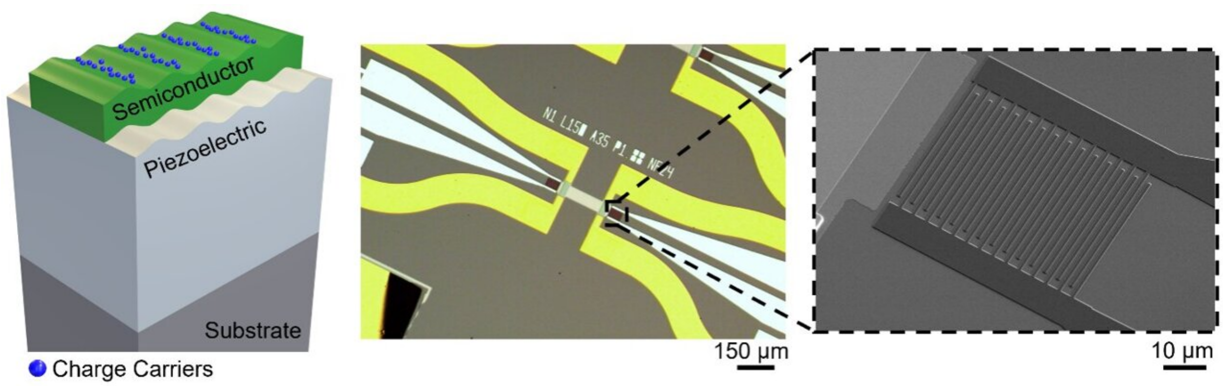

(Left) Schematic of the acoustoelectric heterostructure developed for this study, consisting of a semiconductor layer (for example indium gallium arsenide), a piezoelectric layer (for example lithium niobate), and a substrate (for example silicon). (Center) Microscope image of a fabricated acoustic wave amplifier device with the patterned semiconductor in-between two interdigital transducers used to launch and detect phonons. (Right) Scanning electron microscope image of the fabricated interdigital transducer. Credit: Hackett et al

In recent years, teams of engineers worldwide have been trying to develop acoustic devices based on piezoelectrics (i.e., materials that can produce electricity when mechanical stress is applied to them) integrated with conventional semiconductors. These devices could achieve acoustoelectric effects that could potentially help to improve the performance and reduce the size of radio-frequency electronics.

Researchers at Sandia National Laboratories and University of Arizona have recently developed non-reciprocal acoustoelectric amplifiers that achieve a net gain and low noise during continuous operation. These amplifiers, presented in *Nature Electronics*, are based on a unique three-layer heterostructure comprised of a semiconducting film, a piezoelectric film and a silicon substrate.

"Amplifiers are key components of all information processing systems that boost the size of signals for transmission, detection, and nonlinear processes like mixing." Matt Eichenfield, the researcher who supervised the study, told Tech Xplore. "They're a feature of essentially all signal processing, whether that signal is a needle getting vibrated by the tracks of a record, a radio wave, or photons carrying your internet in an optical fiber. For the first time, we demonstrated a high-performance amplifier for very high frequency sound waves, vibrating billions of times per second."

"All amplifiers inherently add noise to an original signal, thus the key goal for engineers is to add the least amount of noise possible while increasing a signal's power as much as possible," said the study's first author, Lisa Hackett.

The key advantage of amplifiers developed by Eichenfield, Hackett, and colleagues is that they can run continuously with high gain (i.e., ratio of output to input power) adding very little noise to an original signal and without consuming too much power.

"While amplifying gigahertz frequency acoustic waves may sound esoteric, it's definitely not," Eichenfield said. "If you have a 5G cell phone in your pocket, then you have dozens of devices in your pocket that turn gigahertz radio waves into sound waves at the same frequency and back.

"This is because at these very high, gigahertz frequencies, there are many advantages of processing information with sound waves. In particular, they have very low loss, which is critical if you're trying to capture very small signals, and the wavelength of the sound waves is very small (hundreds of times smaller than a human hair), which means the size of devices that can manipulate them are correspondingly small."

The use of sound waves is becoming increasingly prominent in numerous information processing applications. For instance, Amazon Web Services recently published a blueprint for making a quantum computer that uses these sound waves as a key component of its information processing.

So far, however, the only type of radio-frequency acoustic wave signal processing application realized on a large scale has been filtering, which essentially separates signals from other signals or noise based on their frequency. Eichenfield and his colleagues were the first to create an acoustic amplifier that can operate at this high frequency range achieving a remarkable performance.

"Our amplifier can essentially boost the signal power of these gigahertz frequency acoustic waves or phonons 1,000 times while only degrading the signal to noise background by a factor of 2, all while staying on continuously," Eichenfield explained. "Another thing they do, which is harder to understand but may be just as important, is transmit signals going in the wrong direction through the amplifier 300,000 times less than the signals going through the right way.

"Again, this seems esoteric, but you really don't want the signals that reflect in your system to travel backward because they can interfere with all the electronics back upstream. Usually this means you have to place a device called an isolator in front of an amplifier to pass signals going forward and attenuate signals going backward, but these amplifiers do that naturally themselves. This feature is called nonreciprocity, and this is the most nonreciprocal device for surface acoustic waves ever created."

Almost all wireless systems available today process radio wave signals as acoustic waves somewhere in the signal chain. Yet, the benefits of processing acoustic signals have not yet been fully realized. For more than sixty years, researchers have been trying to enhance the performance and functionalities of wireless devices via acoustic signal processing by integrating them with semiconductors.

"Wireless technologies use acoustic wave resonators made from piezoelectric materials to filter signals (separate one signal from all the rest of the signals and noise in the universe)," Eichenfield said. "These piezoelectric filters are workhorses in all wireless systems, and you have dozens in your pocket if there is a 5G cell phone in it.

"However, the ability to provide other functions in those like amplification could vastly increase their utility because you can simultaneously filter the signal, boost up its power, and provide nonreciprocal devices like isolators in the same chip, reducing the overall number of chips it takes to make a whole wireless processing system."

Past studies aimed at developing highly performing acoustic wave amplifiers were unable to produce a device that could operate continuously with large acoustic gain, low acoustic noise, low power consumption and dissipation and operating at the gigahertz frequencies required for many applications.

To achieve this, Eichenfield and his colleagues leveraged a combination of modern material growth, integration and microfabrication techniques. These techniques allowed them to create a system made of multiple thin materials that combined can achieve larger gain and lower noise, dissipating the heat it generates while doing so to prevent the device from overheating.

"This work builds on both a rich body of work starting in the 1970s, which was never really successful in terms of creating a technologically useful device, and our own team's work over the past five years or so," Eichenfield said. "These challenges include figuring out how to integrate very thin, essentially perfect semiconductor materials onto the surface of the piezoelectric materials you need for the acoustic waves, figuring out how to get those materials onto a large amount of a material with high thermal conductivity so it can dissipate the heat without degrading the other features important to the performance, and then just plain figuring out how to actually design the amplifiers for high performance."

In their recent study, Eichenfield and his colleagues set out to identify a strategy that would allow them to modify and optimize an acoustoelectric heterostructure that they had already been working on for many years. Ultimately, they hoped that this would enable their device to continuously amplify acoustic waves at the input, as opposed to needing to turn it off periodically to allow heat to dissipate.

"In past demonstrations, we cycled the power to show the potential of the devices to amplify acoustic waves, but couldn't do that continuously without damaging the devices," said Hackett. "An amplifier that can't be left on continuously has significantly restricted applications compared to one that just stays on all the time."

"Once we found our material and structural modifications worked well enough to produce large acoustic gain while operating continuously, we then sought to achieve gigahertz frequency operation and to evaluate how much gain we could produce and how little noise."

In initial tests, the researchers showed that their acoustoelectric amplifiers can continuously operate at a sound wave frequency of 1 GHz, with a 1,000x gain and adding a limited amount of noise to acoustic signals. They also achieve a nonreciprocal transmission of 300,000x, power consumption of 10 thousandths of a watt, and a considerably small footprint (0.07 mm^2).

"Our amplifiers also have several unique design features," Eichenfield said. "First, we used one of the most piezoelectric materials, lithium niobate, to carry the acoustic waves. This is important because the more piezoelectric the material, the more efficiently you can generate and detect acoustic waves, and the more piezoelectric the material the larger the electric field outside the material that can be used to interact with electrons and produce the acoustoelectric interaction that makes it an amplifier."

The device created by Eichenfield and his colleagues is based on a very thin (50 nm) layer of the semiconductor indium gallium arsenide, which is 2,000 times thinner than a human hair. This layer hosts the electrons that produce the interaction underpinning its amplifying function. The semiconducting layer was then placed on the surface of a lithium niobate film, enabling strong interactions between them.

"The lithium niobate in our amplifiers is also very thin (only 5 micrometers), and it is sitting on a very thick layer of silicon," Eichenfield said. "This layer of silicon does two things. First, it helps confine the waves in the thin lithium niobate, which generates a stronger interaction with the electrons and prevents the acoustic energy from leaking out, and, second, it's a good thermal conductor, which helps remove the heat generated by making the electrons flow in the direction of the acoustic wave, which is how you generate the amplification (when the electrons go faster than the acoustic wave, in particular)."

Remarkably, the team's amplifier can amplify gigahertz frequency sound waves just as well as state-of-the-art microwave amplifiers amplify frequency radio waves, while also exhibiting a remarkably high nonreciprocal transmission. In the future, it could be used to increase the performance and broaden the functionalities of a broad range of wireless systems. So far, the processing of acoustic waves in devices has primarily been performed by specifically designed filters, yet the team's study could open new exciting possibilities.

"There are a lot of other devices that a wireless system must have to process radio waves, like amplifiers, oscillators, isolators, switches, and mixers (devices that change the frequency of signals and also allow you to put on and take off relatively low-frequency information from high frequency 'carrier waves')," Eichenfield said.

"All these components besides filters are made from transistor technologies, which means that you need several different kinds of chips to make the whole radio frequency signal processor, at least one chip based on piezoelectric sound waves and at least one chip based on electronic transistors. What we're doing here is making inroads towards being able to make all of the components in the signal chain acoustic devices and make them all on one chip, which would allow them to be much, much smaller and potentially higher performance."

While the researchers' study is merely a step towards integrating all these components in a single chip, it is a very promising milestone. Ultimately, their efforts could enable the integration of wireless systems in far smaller devices, while also significantly increasing their signal processing power.

In their next work, Eichenfield, Hackett, and colleagues plan to develop some of the other key wireless signal processing components in the acoustic domain, such as mixers. They are also exploring the potential of acoustic wave processing for the development of highly performing quantum computers and quantum network systems. Their acoustic wave amplifiers could be particularly useful for allowing these technologies to amplify and directly read out signals carried as sound waves.

"Another direction we are exploring entails combining these same effects with light," Eichenfield added. "We've shown in a different recent paper that you can drastically improve the performance of a lot of very important on-chip photonic devices if you can do the same things we've done in this work but in materials that are transparent to the light so that the photons can go through the same devices as the phonons; it turns out it's really not a lot of work to make all the materials transparent at the frequencies of light used to process most of the internet's signals (~200 THz). In fact, just simply adding some phosphorous to the indium gallium arsenide does the trick."

More information: Lisa Hackett et al, Non-reciprocal acoustoelectric microwave amplifiers with net gain and low noise in continuous operation, *Nature Electronics* (2023). DOI: 10.1038/s41928-022-00908-6

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