Detection of lattice temperature using gate induced drain leakage in silicon chip

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Abstract - **We report a method and experiment to detect the transport of the lattice phonon generated by hot electrons during the MOSFET operation. By measuring the gated-induced drain leakage (GIDL) current of the MOSFET as a phonon sensor and using a nearby MOSFET as a phonon generator operating in the hot carrier generating bias conditions, we are able to detect the transport of the phonons in the chip. In order to validate the idea, we performed experiments with the 5-transistors scheme, which consists of the 1-phonon sensor and the 4-phonon generators. We measure the increment of the GIDL current which is caused by an arrival of the phonons transported from the phonon generator by using the lock-in technique in the scheme. From the variation of the GIDL current in different distances and the gate bias conditions, we estimate the equivalent lattice temperature on the assumption of the system in near-equilibrium. Moreover, we explain the fundamental principle that the GIDL current can estimate the phonon energy even in non-equilibrium. Additionally, we report that our method can be used to estimate the number of the major phonons generated in the strained silicon technology.**

***Keywords*—Gate induced drain leakage (GIDL), Lattice temperature, Phonon**

I. INTRODUCTION

For the reliability and the performance of semiconductor devices, the temperature (T) increase due to Joule's heating in the chip has been considered as a significant measure of an increase in the phonon energy due to electron-phonon scattering. As these demands, various methods to estimate the temperature on a chip have been reported: for example, the temperature characteristics of a PN diode leakage or a sub-threshold swing in a MOSFET has been used as temperature sensors [1]-[3]. Those methods are all based on the assumption of near-equilibrium for electrons with lattice temperature. This is because, when the phonons generated in the heating device reach the temperature sensor, they are distributed in near-equilibrium and the electrons interact with these phonons. Through this assumption, the equivalent temperature (T_{eq}) is extracted from their current characteristics. In other words, they estimate the lattice temperature with electron temperature.

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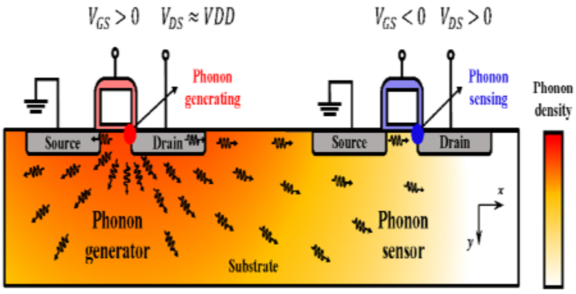
However, in the nano-CMOS era, as the size of the devices has been scaled down, the distance between the device as the heat source (or a phonon generator) and the device influenced by the phonons can be often shorter than the mean free path of the phonon. So the temperature sensor reflects the effect of the electrons and the phonons in non-equilibrium, where the distribution of the electrons and the phonons are quite different from their equilibrium states. Thus, the temperature sensor based on near-equilibrium is inappropriate.

In this paper, we propose the new method which can be used for both near and non-equilibrium state of the phonons. It is feasible by directly observing the reduction in band gap caused by the generated and transported phonons from other phonon sources. It is based on the principle that the phonons generated by the electron-phonon scattering perturb the periodic potential of electrons and consequently cause a shift in the electron energy states [4], [5]. The change of the band gap by the phonons is sensitively measured by the band-to-band tunneling (BTBT) current, since the band gap acts as a tunneling barrier in the BTBT of the electrons [6], [7].

With this principle, we intend to measure the phonons produced in the heat source MOSFET with a nearby phonon sensor based on the BTBT. The sensor based on the BTBT can be implemented by applying the GIDL bias to a MOSFET. In order to check the validity of the suggested idea, the 5-transistors scheme is designed. In section II, we introduce the experiment setup in detail. Additionally, we summarize the underlying physics associated with the relation between the phonon and the band gap by introducing studies about the phonon effect on the electron energy states [4], [8]. In section III, the experimental results are presented and discussed. We present the fundamental principle to estimate the equivalent temperature in near-equilibrium and also the phonon energy in non-equilibrium especially. Finally, we conclude our work in section IV.



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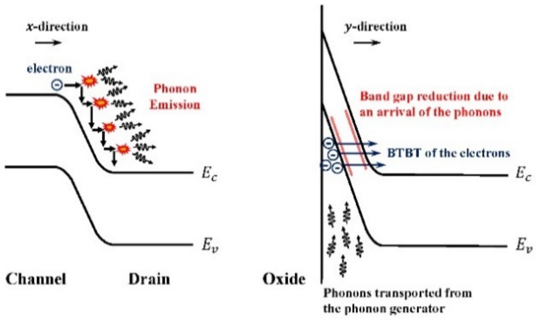

(b) (c)

Fig. 1. (a) n-MOSFET used as a phonon generator and a phonon sensor. (b) Emission of the phonons by hot electrons at the drain side of the channel region on the phonon generator (c) Enhancement of the BTBT due to arrival of the phonons at the gate-to-drain overlap region in the phonon sensor

II. PHONON GENERATOR AND SENSOR

A. Device design for phonon generator/sensor: 5-transistors scheme

An n-MOSFET, for example, can be used as the "phonon generator" since the channel electrons lose their energy by generating phonons at the drain side of the channel region when the n-MOSFET operates under the drain bias condition with VDD [9], [10]. As mentioned above, the phonon sensor based on the BTBT is also implemented with an n-MOSFET by applying the GIDL bias to it. It is because that the leakage current is due to BTBT of the electron [11], [12]. We describe the concepts of a phonon generator and sensor in Fig. 1.

In order to examine the idea experimentally, we designed the 5-transistors scheme as shown in Fig.2. The scheme consists of five n-MOSFETs of which the gate length/width are 180 nm/10 μm and their threshold voltage is around 0.42 V. One of them (the blue-colored gate) is used as the phonon sensor and the others (the red-colored gates) are as the phonon generators. The phonon generators are located at 1.44 μm, 2.88 μm, 4.32 μm and 5.76 μm away from the phonon sensor, respectively. This chip was fabricated by the Skhynix/magnachip 018 process.

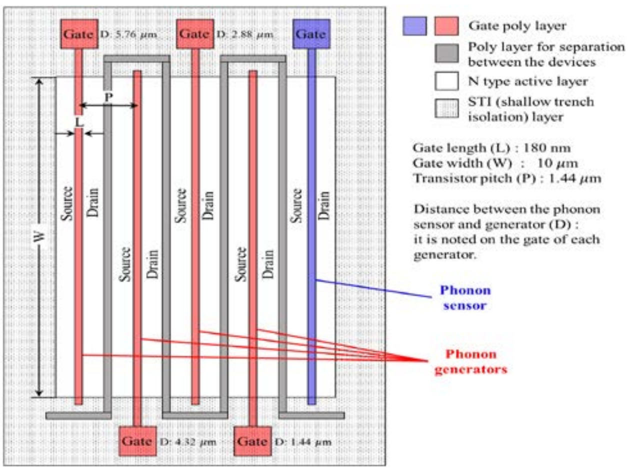

Fig. 2. Layout of the 5-transistors scheme. This scheme consists of the 1-phonon sensor and the other 4-phonon generators

B. Underlying physics between phonon and bandgap

In this section, we summarize the established physics relating the phonons arriving at the phonon sensor and its effect to the band gap reduction of the phonon sensor.

After the generation in the phonon generator, the phonons diffuse into the substrate with relaxation process. The longitudinal optical (LO) phonons, which occupy the major portion of the total phonon modes generated by the hot electrons, are known to break up into other phonon modes with the range of tens of nanometers [13]-[15] and spread through the substrate. Some of the decayed phonons arrive at the phonon sensor in the chip. We express the number of the phonons as $\sum_{\mathbf{q},s} \Delta n_{\mathbf{q},s}$ (where $\mathbf{q}, s$ refers to the phonon mode with wave vector, $\mathbf{q}$, and branch, s).

These phonons perturb the periodic potential of the electrons in the lattice and consequently raise the change in the electron energy state of the phonon sensor. According to the reference [4], [8], the band gap modulated by the electron-phonon effects is expressed with the coefficient $\partial E_{n\mathbf{k}}/\partial n_{\mathbf{q},s}$, which is the contribution from the phonon in the mode $\mathbf{q}, s$ to the electron energy shift, $\Delta E_{n\mathbf{k}}$. As the coefficient tends to be positive for the highest valence-band (n=v, $\mathbf{k}$=0) and negative for the lowest conduction-band (n=c, $\mathbf{k}$=0.84$\mathbf{X}$), one can expect that the net effect due to $\sum_{\mathbf{q},s} \Delta n_{\mathbf{q},s}$ is to reduce the band gap of the phonon sensor. Finally, the reduction in the band gap can be observed by the BTBT of the electrons in the phonon sensor as explained earlier.

C. Experimental setup

In order to detect the phonons with the idea as above mentioned, we applied the lock-in technique into the 5-transistors scheme, as shown in Fig. 3.

At first, a pulsed bias was applied to the gate of the phonon generator during the drain voltage are kept in the steady mode with $V_{\mathrm{DS,gen}}$ of 2 V. The pulse has a frequency of 1 kHz (duty 50%) with a variable pulse amplitude (called $V_{\mathrm{G,amp}}$) from 0 to 3.0 V with a step of 0.2 V. Then the periodic generation of the phonons is expected. The pulse width (0.5 ms) is long enough for the phonon number to be saturated since the response time of the phonon generation of our phonon generator is expected much shorter than the pulse width (under ~10 μs).

The gate and drain voltages of the phonon sensor are kept in the GIDL mode with $V_{\mathrm{GS,sen}}$ and $V_{\mathrm{DS,sen}}$ of -3.5 V and 3 V, respectively, while the phonon generator is in the pulse mode. The GIDL base current without the phonon generation is about 9.1 μA ($I_{GIDL,0}$) but the periodical increment, ΔI_{GIDL}, is added to the GIDL base current. It results from the periodic band gap reduction which is caused by the periodic arrival of the phonons synchronized with the gate pulse period (1.0 ms) in our experiment.

In order to measure the amplitude of the periodic current (ΔI_{GIDL}), the lock-in amplifier is used to take advantage of its high signal-to-noise ratio property. The total GIDL current (I_{GIDL}) response is converted to the voltage signal with a trans-impedance amplifier (TIA) and its output is connected to the input of the lock-in amplifier. The pulse generators and the lock-in amplifier are triggered and synchronized with the reference signal, which has a same frequency of the gate pulse. Finally, the periodic change (ΔI_{GIDL}) in the total GIDL current is extracted from the output value of the lock-in amplifier.

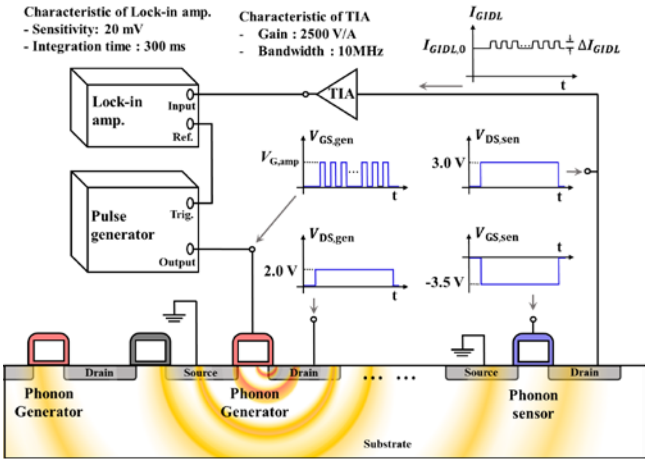

Fig. 3. Experimental set up. The pulse applied to gate terminal of the phonon generator has an amplitude of $V_{\mathrm{G,amp}}$ and frequency of 1 kHz. A trigger (Trig.) synchronized with the gate pulse (output of the function generator) is connected to the reference input (Ref.) of the lock-in amplifier. Simultaneously, the phonon sensor is operated under the GIDL bias. The small plot in this figure describe the voltages on each terminal as a function of time (t).

III. RESULTS AND DISCUSSION

A. Trend of GIDL current in the sensor devices

ΔI_{GIDL} results from the band gap reduction, which is caused by the phonons ($\sum_{\mathbf{q},s}\Delta n_{\mathbf{q},s}$) arriving at the phonon sensor. Thus, the more the phonons arrive at the phonon sensor, the more an increment in the I_{GIDL} is expected. The qualitative dependence of the phonon generation rate in the phonon generator can be estimated from the Synopsys Sentaurus TCAD simulation considering the hydrodynamic model of the carriers [16, 17]. In the simulation, the phonon generation rate can be related with the energy loss rate due to collision with the lattice in the electron energy balance equation. Fig. 4 shows the energy loss rate due to collision as a function of the gate voltage for the devices used for the phonon generator (see Fig. 2) under the constant $V_{\mathrm{DS,gen}}$ of 2.0 V. The total energy loss rate of the channel electrons due to the phonon generation linearly increases with V_{GS} over the threshold voltage. The number of the phonons generated in the phonon generator is expect to have a similar trend.
Fig. 5 shows the experimental results of ΔI_{GIDL} as a function of $V_{\mathrm{G,amp}}$ for the phonon generators located at different distance from the phonon sensor. It is interesting to notice that there exists, at least, the qualitatively trend similar to that shown in Fig. 4, as expected. It is also observed that the further phonon generator away from the phonon sensor operate, the less ΔI_{GIDL} is measured. It means that the phonons generated in the phonon generator spread through the whole substrate by diffusion so the less phonons arrive at the distant sensor receives from the generator.

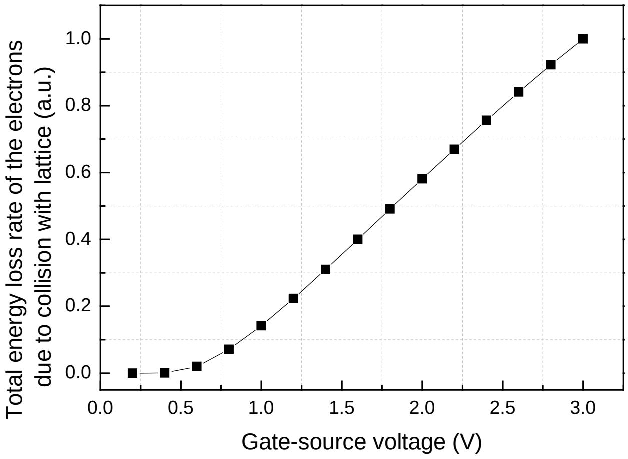

Fig. 4. Total electron energy loss rate due to collision with lattice in the phonon generator versus its gate voltage.

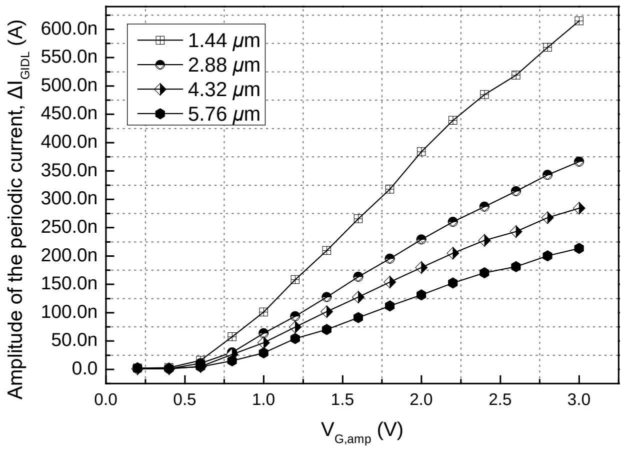

Fig. 5. Periodic increment of the GIDL current ($\boldsymbol{\Delta I_{GIDL}}$) of the phonon sensor as a function of $\boldsymbol{V_{\mathrm{G,amp}}}$ of the phonon generators for different distances (1.44 μm, 2.88 μm, 4.32 μm and 5.76 μm).

B. Conversion from ΔI_{GIDL} to lattice temperature

It is convenient to relate ΔI_{GIDL} to the lattice temperature, T_l, which is frequently used as the indicator of the number of the phonons. However, it is important to notice that T_l is the concept defined in equilibrium.

Since the distances of the phonon sensor from the generators in our chip (as shown in Fig. 2) are longer than mean free path of the phonon as mentioned in section II.B, it might be assumed that the phonons reaching the phonon sensor are in near-equilibrium for each mode ($\mathbf{q}, s$). In other words, the phonon occupation number for each mode can be represented as the equivalent temperature, T_{eq}, by the Bose-Einstein statistics, $n_{\mathbf{q},s}(T)$, as

$$n_{\mathbf{q},s}(T_0) + \Delta n_{\mathbf{q},s} \approx n_{\mathbf{q},s}(T_{eq}) \quad (1)$$

Here, T_0 is the room temperature. Now, in order to estimate T_{eq}, from the ΔI_{GIDL} data in Fig. 5, we performed a separate

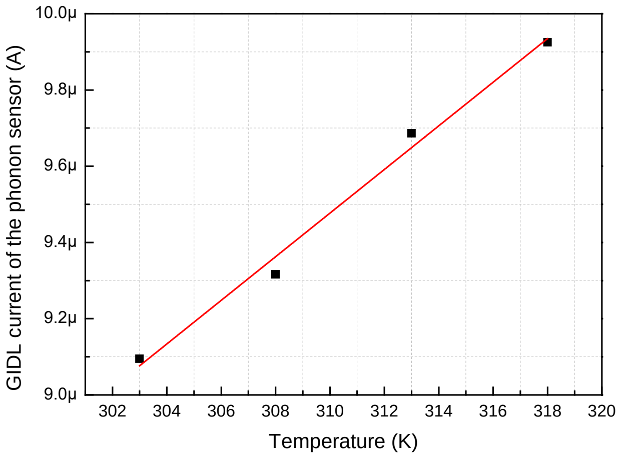

Fig. 6. GIDL current-temperature (I_{GIDL}-T) characteristic of the phonon sensor at different temperature of the wafer on the chuck from 303 to 318 K.

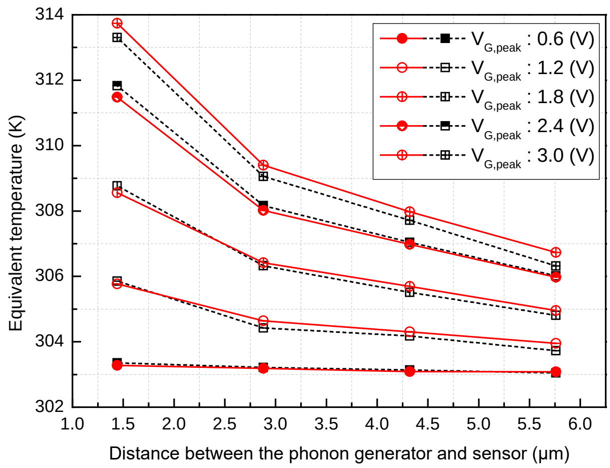

Fig. 7. Equivalent lattice temperature obtained from two different set of the measurement, the GIDL (solid lines) and sub-threshold (dotted lines).

experiment. The GIDL currents are measured by changing the temperatures of the wafer on the chuck as 303, 308, 313, and 318 K. Fig. 6 shows the equilibrium temperature characteristics of the GIDL current under the same bias condition as explained in the section II.C.

Using the data in Fig. 6 and the ΔI_{GIDL} data in Fig. 5, we estimated the lattice temperature of the phonon sensor and plotted it with red solid lines in Fig. 7. As can be seen, temperature increases up to 13 K when a phonon generator 1.44 μm away from the phonon sensor is operated under the 3 V pulsed bias of the gate voltage. In addition, when the $V_{\mathrm{G,amp}}$ is below 0.4 V, it is observed that there is no appreciable amount of the phonon generation. With this equivalent temperature, the number of the phonons at the sensor, $n_{\mathbf{q},s}(T_{eq})$, can be also estimated by the Bose-Einstein statistics.

For comparison, the phonon sensor MOSFET was operated not only in the GIDL mode but also in the sub-threshold mode. Due to the phonons, the sub-threshold current increases as the electron temperature, T_e, increases also following T_l at the phonon sensor. If the electrons are distributed in near-equilibrium for the same T_e as T_l, the increase of the sub-threshold current is a good indicator of the lattice temperature. The black dotted lines in the Fig. 7 represent the temperature obtained from sub-threshold mode in the same manner of the case of the red solid line.

It is worthy of notice that the equivalent temperatures obtained from two different set of the measurement, the GIDL and the sub-threshold mode, are almost the same. It can be understood because the electrons and the phonons are in near-equilibrium for the phonon sensor distant from the phonon generator.

C. New method to estimate phonon energy from ΔI_{GIDL}

The method to estimate the equivalent temperature with the sub-threshold current as mentioned above is not appropriate where the phonons and the electrons are under non-equilibrium. Under the non-equilibrium condition, especially the place where the phonons are not fully relaxed after the generation, the number of the phonon for each mode $(\mathbf{q}, s)$, $n_{\mathbf{q},s}$, cannot be represented by a constant T_{eq} like as (1). In other words, there exist some modes in which a significant amount of phonon occupies. Because the electrons in the place interact these phonons, the distribution of the electrons is also under non-equilibrium as mentioned in section I. Therefore, an increment of the sub-threshold current does not precisely represent the number of the phonons as T_{eq}.

In the case of non-equilibrium, the direct estimation of the phonons energy, U, not by T_{eq} is appropriated. The GIDL current is useful in this regard. At first, by replacing the coefficient $\partial E_{n\mathbf{k}}/\partial n_{\mathbf{q},s}$ with $f_{n,\mathbf{k}}(\omega_{\mathbf{q},s})$, we express the total reduction in the band gap, ΔE_g, due to $\sum_{\mathbf{q},s} \Delta n_{\mathbf{q},s}$ as

$$\Delta E_g = \sum_{\mathbf{q},s} \Delta n_{\mathbf{q},s}[f_{c,0}(\omega_{\mathbf{q},s}) - f_{v,0.84\mathbf{X}}(\omega_{\mathbf{q},s})] \quad (2)$$

where $\omega_{\mathbf{q},s}$ is the frequency of the phonon in mode $(\mathbf{q}, s)$.

Here, it is worthy of note that the electron phonon spectral function, $\sum_{\mathbf{q},s}[f_{c,0}(\omega_{\mathbf{q},s}) - f_{v,0.84\mathbf{X}}(\omega_{\mathbf{q},s})]\delta(\omega - \omega_{\mathbf{q},s})$, is known to be well fitted with $c\hbar\omega g(\omega)$ [14], [18]. Here, $\hbar\omega$ is the phonon energy, $g(\omega)$ is the phonon density of states and c is a proportional constant. It means that the reduction in the band gap can reflect the energy of the phonons arriving at the phonon sensor, ΔU, like as

$$\Delta E_g = c\Delta \mathrm{U} = c\int_0^{\omega_{max}} \Delta n(\omega)\hbar\omega g(\omega)d\omega. \quad (3)$$

In order to relate the phonon energy with the GIDL current, we use the analytical formula for the GIDL current expressed by the effective surface electric field, F, a pre-exponential coefficient A and a coefficient B proportional to $E_g^{3/2}$, as follows.[10]

$$I_{GIDL} = AF\exp(-B/F) \quad (4)$$

In silicon, the coefficient A is known to be relatively independent on temperature [19].

Then, we can relate the measured ΔI_{GIDL} with $\Delta\mathrm{U}$, as follows.

$$\log\left(1+\frac{\Delta I_{GIDL}}{I_{GIDL,0}}\right)\approx-\frac{3B\log_{10}(e)}{2FE_{g0}}\Delta E_g=-\frac{3cB\log_{10}(e)}{2FE_{g0}}\Delta\mathrm{U} \quad (5)$$

where E_{g0} is the band gap at the room temperature. Since the relationship holds for both the equilibrium and non-equilibrium conditions, the coefficient $3cB\log_{10}(e)/(2FE_{g0})$ in (5) can be obtained from the equilibrium temperature characteristic of the GIDL current. For this, $\Delta\mathrm{U}$ in (5) is replaced with $\Delta T\times\partial\mathrm{U}(T)/\partial T$ as

$$\log\left(1+\frac{\Delta I_{GIDL}}{I_{GIDL,0}}\right)\approx-\frac{3cB\log_{10}(e)}{2FE_{g0}}\frac{\partial\mathrm{U}(T)}{\partial T}\Delta T \quad (6)$$

In equilibrium, $\partial\mathrm{U}(T)/\partial T$ can be derived from

$$\mathrm{U}(T)=\int_0^{\omega_{max}}\left(n(\omega,T)+\frac{1}{2}\right)\hbar\omega g(\omega)d\omega \quad (7)$$

and is calculated to be about 1.02×10^{19} $\mathrm{eVcm^{-3}K^{-1}}$. Finally, the coefficient $3cB\log_{10}(e)/(2FE_{g0})$ can be estimated from the measured data in Fig. 6. For our phonon sensor, it has about 2.55×10^{-22} $\mathrm{eV^{-1}}$.

The method is useful in two ways; Firstly, we can estimate the physical constant such as c if we know the value of F and B. Secondly, the coefficient $3cB\log_{10}(e)/(2FE_{g0})$ can be used to estimate the total energy of the phonons in non-equilibrium as well, if ΔI_{GIDL} is measured.

As a comment, our method can be extended to the strained silicon technology which has been adopted for the mobility enhancement. In the strained silicon at low electric fields (under $\sim10^4\,V/cm$), emission of the LO phonon of which the wave vector $\mathbf{q}$ is about $0.3\mathbf{G}$ along $\langle100\rangle$ (we mark this mode with $[0.3\mathbf{G},LO]$) occupies about 90 percent of the total energy dissipated by the electron-phonon scattering in the channel [11], [12]. Therefore, within its mean free path from the operating transistor, it is expected that a substantial amount of the phonon in mode $0.3\mathbf{G},LO$ occurs [20]. Using the coefficient $f_{c,0}(\omega_{\mathbf{q},s})-f_{v,0.84\mathbf{X}}(\omega_{\mathbf{q},s})$ for the strained silicon, the number of the generated phonons, $\Delta n_{0.3\mathbf{G},LO}$, can be related with the measured ΔI_{GIDL} as

$$\log\left(1+\frac{\Delta I_{GIDL}}{I_{GIDL,0}}\right)\approx \frac{3B\log_{10}(e)}{2FE_{g0}}\left[f_{c,0}(\omega_{0.3\mathbf{G},LO})-f_{v,0.84\mathbf{X}}(\omega_{0.3\mathbf{G},LO})\right]\Delta n_{0.3\mathbf{G},LO} \quad (8)$$

In summary, the sensor based on the BTBT can estimate the number of phonons directly, which is not possible in the conventional sensors based on the electron temperature. We expect that our sensor can be useful in the practical condition where devices operate with the electrons and phonons in non-equilibrium and even in the strained silicon substrate.

IV. Conclusions

In this work, we proposed the method to directly detect the phonons generated by hot-electron in the chip with the GIDL current. We adopted the principle that the phonons reduce the band gap and consequently increase the BTBT rate of the electrons. By using the 5-transistors scheme and adopting the lock-in technique, we showed that the generated and propagated phonons from the phonon generator can be detected by the GIDL current of the phonon sensor. In the scheme, the phonons both under non-equilibrium and near-equilibrium can be identified. When the phonon generator operates at a position farther from the phonon sensor than the order of the phonon mean free path, the phonons at the phonon sensor are under the near-equilibrium condition. In such a case, the equivalent temperature of the phonon distribution can be estimated by comparing the increment of the current of the phonon sensor with the temperature characteristic of the GIDL current separately obtained from the equilibrium condition (as shown in Fig. 6). Even in the non-equilibrium condition where the generated phonons do not fully decay into near-equilibrium, our method can be extended to estimate the energy of the phonons. Additionally, we expect that the phonon sensor based on the BTBT can estimate the number of the phonon in mode $0.3\mathbf{G},LO$ dominantly generated in the strained silicon.

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