Ultrashort Pulse Detection and Response Time Analysis Using Plasma-Wave Terahertz Field-Effect Transistors

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Abstract—We report on the response characteristics of plasmonic terahertz field-effect transistors (TeraFETs) fed with femtosecond and picosecond pulses. Varying the pulsewidth ($t_{pw}$) from $10^{-15}$ s to $10^{-10}$ s under a constant input power condition revealed two distinctive pulse detection modes. In the short pulse mode ($t_{pw} < L/s$, where $L$ is the gated channel length and $s$ is the plasma velocity), the source-to-drain voltage response is a sharp pulse oscillatory decay preceded by a delay time on the order of $L/s$. The plasma wave travels along the channel like the shallow water wave with a relatively narrow wave package. In the long pulse mode ($t_{pw} > L/s$), the response profile has two oscillatory decay processes and the propagation of plasma wave is analogous to an oscillating rod with one side fixed. The ultimate response time at the long pulse mode is significantly higher than that under the short pulse conditions. The detection conditions under the long pulse mode are close to the step response condition, and the response time conforms well to the analytical theory for the step function response. The simulated waveform agrees well with the measured pulse response. Our results show that the measurements of the pulse response enable the material parameter extraction from the pulse response data (including the effective mass, kinematic viscosity, and momentum relaxation time).

Index Terms—Material parameter extraction, plasma-wave electronics, pulse detection, response time, terahertz field-effect transistors (TeraFETs).

I. INTRODUCTION

Plasma-wave terahertz field-effect transistors (TeraFETs) are recognized in recent decades as a promising candidate for terahertz (THz) applications [1], [2]. TeraFETs have been developed in various material systems [3]–[6] and show the potential in such fields as THz detection [7], generation [8], imaging [9], and wireless communication [10]. To accelerate the commercialization of those THz applications, one of the key efforts is the detection and characterization of short pulses [7], [11].

The generation of high-power ultrashort pulses in the THz range is crucial for the ultrafast time-domain spectroscopy [12]–[14]. To monitor the pulsed sources, high-quality subpicosecond detectors are required. Schottky diodes [15], [16] and quantum-engineered devices [17], [18] were utilized in ultrashort THz pulse detection and became the most commercialized devices in the relevant field. However, the operation of those devices requires strict condition (including, in some cases, cryogenic cooling) and has limited operating ranges [13], [17], [18]. Plasma-wave THz detectors are not subject to those limitations [19] and have the potential of reaching better performance as THz pulse detectors.

Fig. 1 shows the structure of a two-dimensional electron gas (2DEG) TeraFET and the equivalent biasing circuit. A pulsed or continuous-wave THz signal shining onto the TeraFET excites the oscillations in gate voltage, resulting in the electron...
density oscillations (plasma waves) in the TeraFET channel. These oscillations generate a voltage response signal $U_d(t)$. We use this detected response for the THz excitation characterization.

Compared with more conventional THz detectors, plasmonic TeraFETs’ advantages include tunability, high responsivity, and operation up to at least 6 THz and demonstrated potential for THz sources [2, 20]. Besides, the response signals of plasmonic TeraFETs contain the information from the TeraFET materials suitable for materials characterization and 2D/3D parameter extraction [7]. Plasmonic TeraFETs can also be used as broadband THz pulse emitters and mixers [8, 21].

In this work, we explore the potential of plasmonic TeraFETs as ultrashort pulse detectors. By focusing on the previously unknown characteristics such as pulsewidth dependence of response time and material parameter extraction, we aim to enrich the basic knowledge and exploit more applications of TeraFET pulse detectors.

II. BASIC EQUATIONS

A 1-D hydrodynamic model is employed in this work to explore the excitation of plasma waves and response features in gated plasmonic TeraFETs. Five material systems, namely p-diamond, n-diamond Si, GaN, and InGaAs, are implemented in this study. The corresponding material parameters are listed in Table I [6], [7], [22]–[32].

The governing hydrodynamic model equations are [4], [33]

$$\frac{\partial n}{\partial t} + \nabla \cdot (nu) = 0$$

$$\frac{\partial u}{\partial t} + (u \cdot \nabla)u + \frac{e}{m} \nabla U + \frac{u}{\tau} - v\nabla^2 u = 0$$

$$\frac{\partial \theta}{\partial t} + \nabla \cdot (\theta u) - \frac{\nu}{C_v} \nabla^2 \theta - \frac{mv}{2C_v} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \delta_{ij} \frac{\partial u_k}{\partial x_k} \right)^2 = \frac{1}{C_v} \left( \frac{\partial W}{\partial t} \right)_c + \frac{mu^2}{C_v \tau}$$

where $n$ is the carrier density and $u$ represents the hydrodynamic velocity. $U$ is the gate-to-channel potential defined as $U = U_0 - U_{ch}$, where $U_0$ and $U_{ch}$ are the gate bias above threshold and the channel potential, respectively. In the simulation, we use gradual channel approximation ($CU = e\eta$), where $C$ is the barrier layer capacitance fixed at 0.56 $\mu F/cm^2$ [4] to associate $U$ and $n$. Besides, $\tau = \mu mL$ is the momentum relaxation time of carriers, where $m$ and $\mu$ represent the effective mass and the mobility, respectively.

In the energy equation (3), $\theta = k_BT$ represents the carrier temperature in electronvolt, $\chi$ is a normalized heat conductivity defined as $\chi = \kappa/m$ ($\kappa$ is the heat conductivity), $C_v$ is the thermal capacitance, and $C_v = (\partial \Sigma/\partial \theta)_n$ [7], [33], where $\Sigma = \theta F_1(\xi)/F_0(\xi)$ is the average internal energy, $F_1(\xi)$ is the Fermi integral, $\xi = \ln(\exp(E_F/k_BT) - 1)$ is the chemical potential, $E_F = k_BT_F = \hbar^2/nm$ is the Fermi energy, $W$ is the total energy, and $(\partial W/\partial t)_c$ represents the collision term of $\partial W/\partial t_c$, which can be expressed by $(\partial W/\partial t)_c = (\partial \Sigma/\partial \theta)_n - m\nu^2/\tau$. Furthermore, $v$ is the viscosity of the two-dimensional electron/hole gas (2DEG/2DHE), which is related to the carrier density and temperature. When the temperature $T$ is much lower than the Fermi temperature $T_F$, $\chi$ and $v$ are given by [4], [7], [33]

$$v(T) = \frac{2\hbar}{\pi m T^2} \frac{1}{\ln(2T/T_F)} \quad (T < T_F)$$

$$\frac{\chi(T)}{\chi(T_F)} = \frac{4\pi \hbar T_F}{3m T_T \ln(2T/F_T)} \quad (T < T_F).$$

Generally, $T < T_F$ holds for relatively large gate bias (e.g., $U_0 > 2.3\ V$ for p-diamond TeraFETs), at which the viscosity and heat conductivity could be large. For relatively small $U_0$, $T > T_F$, and we use $v(T = T_F)$ and $\chi(T = T_F)$, which are constant values [4].

The boundary condition that we use is an open-drain condition [4], [19]: $U(0, t) = U_0$ and $J(L, t) = 0$, where $U_0(t)$ represents the pulsed small-signal voltage induced by the incoming radiation and $J$ is the current flux density. This boundary condition agrees with the typical biasing regime shown in Fig. 1(b). It is worth noting that $U_0(t)$ is used to model the excitation of gate-to-channel voltage by the external radiation, and such modeling has been proved to be effective in previous studies [4], [19], [21], [34]. Besides, in this work, we only consider the detection of single-pulse signals, i.e., $U_0(t)$ contains only one pulse without repetition. Also, all the pulses considered are square-shaped. Thus, $U_0(t)$ can be expressed by $U_0(t) = U_{am}(u(t) - u(t - t_{ps}))$, where $U_{am}$ is the amplitude of the pulse voltage, $u(t)$ is the unit step function, and $t_{ps}$ is the pulsewidth.

The above hydrodynamic model is valid when $1/\tau_{ee} \gg 1/\tau$ [4], [7], [33], [35], [36], where $\tau_{ee}$ is the electron–electron scattering rate and $\tau$ represents the momentum relaxation time. We have checked, by calculating the value of $\tau_{ee}$ [37], that this condition is met in this study. More detailed introductions of the hydrodynamic model can be found in [4], [33], and [36]. The results obtained from the hydrodynamic model

| Material | $m/m_0$ | $\mu$ (300 K) | $\tau$ (300 K) | Reference |
|----------|---------|---------------|----------------|-----------|
| p-diamond | 0.74    | 5300          | 2.23           | [6, 22, 23] |
| n-diamond | 0.36    | 7300          | 1.50           | [6, 22, 24] |
| Si        | 0.19    | 1450          | 0.157          | [25-27]   |
| AlGaN/GaN | 0.24    | 2000          | 0.273          | [28-30]   |
| AlGaAs/InGaAs | 0.041 | 12000    | 0.280          | [7, 31, 32] |

*Note: $m$, $m_0$ are the 2D effective mass of carriers and the free electron mass, respectively. $\tau$ (in ps) and $\mu$ (in cm$^2$/V$\cdot$s) are the momentum relaxation time and the mobility of carriers, respectively.*
The amplitude of voltage peak decays with time. Those features indicate that the device is operated at a plasmonic resonant regime [7], [19], [43]. Fig. 3(b) shows the temporal response waveform at the long pulse mode. Unlike the short pulse case, two oscillatory decay processes are observed in the voltage response waveform. One decay process is within the pulsation period, and the other is initiated right after the incoming pulse ends. This phenomenon has never been reported in previous studies. Furthermore, compared to the short pulse case, the voltage response pulses in Fig. 3(b) are much wider, and the shape of pulses resembles the square pulse.

To better understand the mechanisms underlying two detection modes, we trace the voltage distribution profile along the channel at several key moments, as shown in Figs. 4 and 5. Fig. 4 shows the spatial voltage ($U(x)$) profile when $t_{pw} = 10^{-14}$ s. As seen, a voltage peak is generated near the source side ($x = 0$) at $t = 0.1$ ps, and then, it moves rightward toward the drain ($x = 130$ nm). The movement of voltage wave is a reflection of the propagation of plasma wave in the channel, with a speed close to plasma velocity $s \approx \sqrt{eU_0/m}$. When the wave precursor hits the boundary, it gets reflected and changes direction like shallow water [44], as shown in Fig. 4(a) and (b). When reaching the source side, the polarity of the wave reverses due to the fixed source voltage, as shown in Fig. 4(b). Those features clearly demonstrate that the device is operating at plasmonic resonant mode.

Fig. 5 shows the propagation characteristics of plasma wave for a long pulse ($t_{pw} = 10^{-11}$ s). As presented in Fig. 5(a), the voltage ramps up from the source to the drain in the beginning phase. When the wavefront reaches the drain, the voltage level there continues to ramp up, and then, the

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**III. RESULTS AND DISCUSSION**

**A. Short Pulse Versus Long Pulse**

By varying the pulsewidth of incoming single-pulse signal from $10^{-15}$ to $10^{-10}$ s under a constant input power condition (i.e., $U_{am}^2 t_{pw}/R_{ch} = \text{constant} = 10^{-22}$ $\text{V}^2 \cdot \text{s}/\text{R}_{ch}$, where $R_{ch}$ (in $\Omega$) is the channel resistance), the effect of pulsewidth on the response characteristics of TeraFETs is investigated. In the simulation, two distinctive response modes are observed: short pulse mode, in which $t_{pw} \ll L/s$, and the long pulse mode with $t_{pw} > L/s$. We first take a look at the temporal profiles of voltage response $U_{ds}$ under the short and long pulse conditions, taking $t_{pw} = 10^{-14}$ s and $t_{pw} = 10^{-11}$ s cases as examples. The results are presented in Fig. 3. As shown in Fig. 3(a), some sharp voltage response peaks are observed, and those peaks are generated after the pulsating period due to a short pulsewidth of input signal. A delay time $T_d$ on the order of $L/s$ is observed between the pulse and the first response peak, which is a signature of plasmonic ballistic transport in collision-dominated devices [7]. Besides, the amplitude of voltage peak decays with time. Those features indicate that the device is operated at a plasmonic resonant regime [7], [19], [43].
and (b) 10–11.8 ps, for p-diamond TeraFET attpw

trend of wavefronts and the sequence of steps, respectively.

(a) 0.1–0.9 ps and (b) 0.9–1.7 ps, for p-diamond TeraFET at tpw

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and viscosity, and the amplitude of the voltage oscillations

the energy of the wave gradually dissipates due to the friction

it reflects and propagates back. As the propagation continues,

propagation process. When the reverse wave hits the source,

voltage rise spreads leftward and creates a reversed wave

propagation process. When the reverse wave hits the source,

Fig. 5. Spatial profiles of voltage (U – U0) for time periods:

(a) 0.1–1.7 ps and (b) 0.9–1.7 ps, for p-diamond TeraFET at tpw

The green arrows and numbers within show the propagation
trend of wavefronts and the sequence of steps, respectively.

Fig. 4. Spatial profiles of voltage (U – U0) at different moments:

(a) 0.1–0.9 ps and (b) 0.9–1.7 ps, for p-diamond TeraFET at tpw

attenuates with time. This dynamics of voltage distribution is

more like a waving rod with one side fixed, which is very
different from the short pulse case shown in Fig. 4. Fig. 5(b)

shows the spatial voltage profiles at some moments of time

right after the pulsating phase. One can see that the voltage

at the source side falls due to the quenching of external

excitation. This leads to the destabilization of the system and

consequently initiates another wave propagation process. Thus,
two oscillatory decay processes are observed in Fig. 3(b).

The two distinctive wave propagation mechanisms determine

the ultimate response time, which is a very important

parameter for pulse detection. For weak incoming signals, the

analytical response characteristics are evaluated by solving the

linearized hydrodynamic equations and getting the solution in

the form of \( \sum_{n=0} A_n \exp(\sigma_n t) f_n(x) \), where \( \sigma_n \) is the nth order attenuation factor [7]. The analytical response time \( \tau_r \)
can be approximated by the first-order solution, i.e., \( \tau_r = \text{Re} [1/|\sigma_1|] \). To calculate the response time from the simulation
data, we could fit the temporal voltage response into a periodic
oscillatory decay \( \exp(-t/\tau_r) \cos(2 \pi t/\tau_r + \phi) \), where \( \tau_r \) is the period of oscillation \( \sim 2L/s \). However, at low viscosity, the
higher order modes become nonnegligible and such fitting
fails [4], [7]. To address this problem, we extract the peak
points in the response curve and then do the exponential decay
fitting to get the response time.

Fig. 6 shows the variation of response time with the
pulselength for the TeraFETs fabricated using five different
materials systems. As seen, for all the TeraFETs, the general
evolution trends of \( \tau_r \) are identical. When \( t_{pw} \ll L/s \), the response time is relatively short and keeps almost unvaried
with the increase of \( t_{pw} \). As \( t_{pw} \) approaches \( L/s \), the response time experiences a sharp increase and then stabilizes as
\( t_{pw} \) rises beyond \( L/s \). This indicates that the unique wave
propagation under the long pulse mode leads to a significant
increase in response time compared to short pulse cases.

B. Feature Size Dependence

To further evaluate the pulse detection performances of
TeraFETs, we study the feature size (channel length)
dependence of response time. Fig. 7 shows the channel
length dependence results, taking p-diamond TeraFET as the example. As shown in Fig. 7(a), as \( L \) increases
from 20 to 130 nm, the response time at \( t_{pw} = 10^{-14} \) s.

For \( t_{pw} = L/s \) cases, a dramatic increase is observed when \( L \)

rises from 20 to 65 nm. However, as \( L \) increases further, the response time is saturated and no longer varies with \( L \).

To better understand such evolution trend, Fig. 7(b) plots the response time as a function of \( L \) under four different values of
pulselength. The analytical curve is also included in this figure.

As mentioned earlier, the analytical solution is obtained by
solving the linearized hydrodynamic equations in the form of

\( U(x, t) = \sum_{n=0} A_n \exp(\sigma_n t) f_n(x) \) and \( \tau_r \approx 1/|\text{Re}(\sigma_1)| \) (first-order approximation). The value of \( \sigma_n \) is given by [4], [7]

\[
\sigma_n = \frac{1}{2} \left[ -\left( \frac{1}{\tau_r} + \frac{\pi^2 n^2}{4L^2} \right) \pm \sqrt{\left( \frac{1}{\tau_r} + \frac{\pi^2 n^2}{4L^2} \right)^2 - \frac{2\pi^2 n^2}{L^2}} \right]
\]

\( n = 1, 3, 5, \ldots \) \quad (6)
Fig. 6. Response time versus pulsewidth for (a) TeraFETs of five materials under $U_0 = 0.1 \text{ V}$, $T = 300 \text{ K}$, and $L = 130 \text{ nm}$. The dashed lines and dashed–dotted lines illustrate the response time variation for the first and second decay processes, respectively. (b)–(f) Separated response profiles for p-diamond, n-diamond, Si, InGaAs, and GaN TeraFET, respectively. The horizontal dotted arrow lines and vertical dashed arrow lines show the values of $2\tau$ and $L/s$ for different materials (color-coded), respectively. The units of $\mu$ and $\nu$ are $\text{cm}^2\cdot\text{V}^{-1}\text{s}^{-1}$ and $\text{cm}^2\cdot\text{s}^{-1}$, respectively.

Fig. 7. (a) Response time versus pulsewidth under three different channel lengths. (b) Response time versus channel length under four different pulsewidth values for p-diamond TeraFETs. $U_0 = 0.1 \text{ V}$ and $T = 300 \text{ K}$.

As shown in Fig. 7(b), for short pulse cases ($t_{p_w} = 10^{-14}$ and $10^{-13} \text{ s}$), the response time rises with increasing $L$, but the values deviate from the analytical prediction. For long pulse cases ($t_{p_w} = 10^{-12}$ and $10^{-11} \text{ s}$), a sharp increase in response time at around $L = 20–60 \text{ nm}$ is observed, and the simulation values agree with the analytical curve. This result is expected since the analytical solution is obtained by setting an arbitrary initial condition and solving its transient response of linearized hydrodynamic equations, in which a quasi-steady-state condition is assumed [4]. In other words, the analytical theory is targeted on the step function input. For TeraFETs operated at a long pulse mode, the condition is close to the step function input during each decay process. Therefore, the calculated response times generally conform to the analytical values. For short pulse cases, however, the external excitation is extinguished before the initial plasma wave reaches the drain. Therefore, the voltage profile along the channel does not completely follow the $U(x, t) = \sum \exp(\sigma_n t) f_n(x)$ form. This explains why the simulation curves deviate from the analytical curve for the short pulses. In addition, since the plasma waves in the short pulse mode appear to be less confined in the channel compared to those in the long pulse cases, they are more subject to the electronic fluid friction (i.e., scattering) or viscosity and thus decay more quickly, as shown in Fig. 3. This might be the reason why the response time at short pulse mode is much smaller compared to that of the large pulse mode.

Now, we briefly discuss the variation trends of response time shown in Fig. 7. According to the analytical theory, under the high mobility condition ($\tau \gg L/s$), the expression of $\tau_r$ can be approximated by

$$\tau_r \approx \frac{2\tau}{1 + \pi^2 \nu \tau / 4L^2} \quad (\tau \gg L/s, t_{p_w} > L/s).$$

At relatively low $L$, the term $\pi^2 \nu \tau / 4L^2$ is very large, and thus, the response time is relatively short. This indicates a
strong viscous loss (corresponding to the viscous regime [43]) in short-channel devices. As \( L \) increases, \( \pi^2 v r / 4L^2 \) decreases rapidly, and a sharp increase in \( \tau \) is observed. If \( L \) increases further, \( \pi^2 v r / 4L^2 \) drops to very small values so that \( \tau_r \rightarrow 2\tau \) and \( \tau \) becomes less \( L \) dependent. This explains why \( \tau \) tends to saturate for the high \( L \) values for long pulse cases. It is worth noting that in the experimental measurement of [38], the response time is about 0.53 ps. This value agrees well with the analytical prediction by (7) (0.51–0.54 ps) under similar operating conditions (\( m = 0.041m_0 \), \( \mu = 1.2 \text{ m}^2/\text{Vs} \), \( L = 130–220 \text{ nm} \), and \( \nu = 26 \text{ cm}^2/\text{s} \)).

As regards the short pulse cases, it is noticed from Fig. 7(b) that the values of \( \tau_r \) for \( t_{pw} = 10^{-14} \text{ s} \) and \( t_{pw} = 10^{-13} \text{ s} \) cases are still on the order of momentum relaxation time and have a very weak \( t_{pw} \) dependence. Also, \( \tau_r \) appears to follow an \( L^{0.5} \) law. Therefore, we propose a new semiempirical expression of \( \tau_r \):

\[
\tau_r \approx \frac{2\tau}{1 + \pi^2 v r / 4L^2} \sqrt{\frac{L}{2\tau \nu}} \left( \tau \gg L/s, t_{pw} \ll L/s \right). \tag{8}
\]

The term \((L/2\tau)^{0.5}\) accounts for the plasmonic acceleration in the short pulse mode. The comparison between the results of (8) and the simulation data is given in Fig. 8. As seen, a fair agreement is achieved between the simulation points and the analytical curve.

**C. Parameter Extraction From the Voltage Response Data**

Our results show that the response of a TeraFET to variable width pulses should allow for the materials parameter extraction.

1) **Extraction of Effective Mass** \( m \): In order to get the effective mass \( m \), the delay time \( T_d \) is used. Under the resonant regime, the delay time \( T_d \) is in fact the time for plasma waves to travel from source to drain, so \( T_d \) should be on the order of \( L/s \). The approximate expression of \( s \) is given by \( s \approx s_e = \sqrt{q(t e U_0/m)} \). For a more accurate calculation, one also needs to consider the contribution of pressure gradient (acoustic velocity \( s_{ac} \)), \( s_{ac} = (k_B T/m)^{0.5} \) (for nondegenerate case) so that

\[
s = (s_e^2 + s_{ac}^2)^{0.5} \tag{7}
\]

Then, we obtain the expression for \( T_d \):

\[
T_d \approx \frac{L}{s} = L \sqrt{\frac{m}{eU_0 + k_B T}}. \tag{9}
\]

Therefore, the effective mass can be obtained by plotting the \( T_d \) versus \( L \) fitting curve and extracting the slope of curve. Fig. 9 shows both simulation and analytical data of \( T_d \) as a function of \( L \) for p-diamond TeraFETs at \( t_{pw} = 10^{-14} \text{ s} \). As seen, the simulation results show a very good agreement with the analytical prediction. The linear fitting of the simulation points gives a slope \( k = 5.77 \times 10^{-6} \text{ s/m} \), yielding \( m = (eU_0 + k_B T)k^2 = 6.711 \times 10^{-31} \text{ kg} = 0.737m_0 \), which is very close to the value used in the simulation (\( m = 0.74m_0 \)). For other \( t_{pw} \) values and other materials under the short pulse mode, similar accuracy is obtained using (9) to extract the effective mass.

It should be noted that (9) is valid only for the above-threshold condition. For subthreshold operation, the approximate expression of \( s \) changes to \( s = ((1 + \eta)k_B T/m)^{0.5} \). Then, the equation for \( T_d \) becomes

\[
T_d \approx \frac{L}{s} = L \sqrt{\frac{m}{(1 + \eta)k_B T}}. \tag{10}
\]

Besides, if the plasmonic FET contains an ungated region, we may need to add another term, \( L_{ug}/s_{ug} \), to account for the additional delay contributed by the ungated region (\( L_{ug} \) and \( s_{ug} \) are the length and average wave speed of the ungated region, respectively). Accounting for the ungated regions would result in the reduction of the calculated effective mass that provides the best agreement with the experimental data.

2) **Extraction of \( \nu \) and \( \tau \)**: The kinematic viscosity \( \nu \) and the momentum relaxation time \( \tau \) are two key parameters that determine the performance of the plasmonic devices. The momentum relaxation time is directly associated with the decay of plasma waves and thus determines the response performance of TeraFETs in both continuous-wave detection and pulse detection mode [4], [7], [19], [42]. The viscosity also has a significant impact on the amplitude of the response and the decay speed of plasma waves. Also, the value of \( \nu \) determines the proportion of high-order harmonics of the
response signal \[7\]. Rewriting \(7\), we get

\[\tau_r \approx \frac{2\tau}{1 + \pi^2\nu/4L^2} = \frac{1}{2}\tau = \frac{1}{2\nu} + \frac{\pi^2}{8} \frac{1}{L^2}.\]  

(11)

By plotting \(\tau_r^{-1}\) versus \(L^{-2}\) (for the long pulse data), we could get \(\nu\) from the intercept and \(\tau\) from the slope.

Fig. 10 shows the simulation and analytical curves of \(\tau_r^{-1}\) with varying \(L^{-2}\). It can be seen that the simulation data generally agree with the analytical curve. For \(L_{puw} = 10^{-11}\) s case, the intercept and slope of fitting curve are 2.209 \(\times\) 10^{11} s^{-1} and 1.328 \(\times\) 10^{-4} m²/s, respectively, which correspond to \(\tau = 2.263\) ps and \(\nu = 1.076\) cm²/s. For \(L_{puw} = 10^{-12}\) s case, the data from the fitting curve give \(\tau = 2.196\) ps and \(\nu = 1.658\) cm²/s. Comparison with the data used in the simulation (\(\tau = 2.233\) ps and \(\nu = 1.436\) cm²/s) shows that this method gives quantitatively accurate \(\tau\) and qualitatively accurate \(\nu\) values. We also used the same method to extract values of \(\nu\) and \(\tau\) for other TeraFETs, and similar parameter accuracy was obtained.

Using the abovementioned method, we can also obtain the temperature variation of \(\nu\), which is crucial for the characterization of TeraFET materials. In our simulation, the kinematic viscosity is obtained from (4) for degenerate condition \((T < T_F)\). For nondegenerate case, the viscosity is fixed at \(\nu(T = T_F)\) given by (4). For p-diamond, \(T_F = 13.1\) K, and thus, the viscosity starts to increase after \(T\) drops below 13.1 K. Fig. 11 shows both simulation and analytical results of \(\nu\) versus \(T\) at low-temperature region. As seen, the calculated viscosities conform well to the analytical curve under the cryogenic temperature. This proves that the temperature variation of \(\nu\) can be obtained from the voltage response signals of various temperatures.

### IV. Conclusion

The hydrodynamic simulations show that the response of plasmonic TeraFETs to ultrashort pulse signals is strongly affected by the width of the incoming pulse \((L_{puw})\). In the short pulse mode \((L_{puw} < L/s)\), where \(L\) is the channel length and \(s\) is the plasma velocity), the source-to-drain voltage response is a sharp pulse oscillatory decay preceded by a delay time on the order of \(L/s\). The plasma wave travels along the channel like the shallow water wave with a relatively narrow wave packet. In the long pulse mode \((L_{puw} > L/s)\), the response profile has two oscillatory decay processes and the propagation of plasma wave is analogous to an oscillating rod with one side fixed. The ultimate response time at the long pulse mode is significantly larger than that under the short pulse conditions. The response time under the long pulse mode conforms well to the analytical theory for the step function response since the detection conditions under the long pulse mode are close to the step response condition. The simulated waveform agrees well with the measured pulse response.

Our results could be used for the material parameter extraction from the pulse response data. The effective mass of the 2DEG carriers can be extracted from the delay time data, and the values of kinematic viscosity and momentum relaxation time can be obtained from the response time results under the long pulse mode regime. Using the abovementioned method, it is also possible to extract the temperature dependence of the viscosity, which is very important for the characterization of 2DEG materials.

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