P-diamond Plasmonic TeraFET Detector

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***Abstract*—Hydrodynamic modeling of p-diamond, Si, InGaAs/GaAs, and AlGaN/GaN TeraFETs reveal the potential and advantages of p-diamond TeraFETs for applications in the 240 to 340 GHz band and, therefore, for potentially beyond 5G and IoT applications. Our numerical results show that the p-diamond TeraFET could enable resonant detection in this band in contrast to other material systems. The p-diamond TeraFET have a high detection sensitivity in a large dynamic range. The diamond response characteristics can be adjusted by changing the gate length *L* and tuning the gate bias.**

I. INTRODUCTION

THE plasma-wave terahertz field-effect transistors (TeraFETs) have been implemented in silicon, InGaAs, III-N, graphene and many other materials. Recently, p-diamond has been proposed as another promising candidate for plasmonic THz applications [1].

Diamond has a large effective mass, large optical phonon energy, and high carrier mobilities, which give rise to a very long momentum relaxation time (τ) and allow diamond to meet the plasmonic resonance condition $\omega_p\tau > 1$, where ω_p is the fundamental plasma frequency. With a high τ, the plasmonic resonance can be achieved at above ~200 GHz [1], making diamond promising for THz detection in the 240 GHz and ~600 GHz windows allocated for beyond 5G THz communications.

Compared to n-diamond, p-diamond has a larger effective mass ($m_{\mathrm{eff}} = 0.74m_0$) and a comparable maximum carrier mobility (as high as ~5300 $\mathrm{cm^2{\cdot}V^{-1}s^{-1}}$). Therefore, here we focus on the characteristics of p-diamond as a TeraFET material.

II. RESULTS

With a large effective mass, the critical τ (or critical mobility) required for resonant operation in p-diamond devices should be relatively low [1]. Here we exam the minimal resonant mobility in TeraFETs using the minimum response time method, i.e. measuring the response time (τ_r) of TereFETs and finding the mobility at which the minimum τ_r is reached [2-4]. Fig. 1 presents τ_r as a function of mobility μ in TeraFETs fabricated using 4 material systems. Both simulation and analytical results are given. The τ_r values are calculated by feeding an ultra-short (5×10^{-14} s in this case) square pulse signal to the device and analyzing the voltage response [2]. The analytical theory was proposed in [5] and [2], in which the response is obtained by solving the linearized hydrodynamic equations in the form of $U(x, t) = \sum_{(n)}A_n\exp(\sigma_n t)f_n(x)$, and take $\tau_r \approx 1/\mathrm{Re}(|\sigma_1^+|)$ (first-order approximation). σ_n has the form

$$\sigma_n^{\pm} = \frac{1}{2}\left[-\left(\frac{1}{\tau}+\frac{\pi^2\nu n^2}{4L^2}\right) \pm \sqrt{\left(\frac{1}{\tau}+\frac{\pi^2\nu n^2}{4L^2}\right)^2 - \frac{\pi^2 s^2 n^2}{L^2}}\,\right] \qquad (1)$$

$$n = 1, 3, 5, \ldots$$

As shown in Fig. 2(a1), the response time curves decrease with μ, reaches a minimum, and then rises and saturates. In the low mobility regime, the plasma waves are overdamped, and the value of τ_r is on the order of $L/\mu U_0$ (where U_0 is the DC gate bias above threshold), so that $\tau_r \propto \mu^{-1}$ [2]. The high-mobility mode corresponds to the resonant plasmonic operation regime. The minimum τ_r is reached at the transition mobility between two regimes (μ_T) [2]. Therefore, μ_T represents the lower limit of μ required for reaching resonant mode. As seen, the τ_r curves shown in Fig. 2(a1) agree with the analytical ones in Fig. 2(a2). Also, as shown in Fig. 2(c1), p-diamond TeraFET has the lowest μ_T among 5 material systems, and the value of μ_T for p-diamond (700 $\mathrm{cm^2{\cdot}V^{-1}s^{-1}}$) is much lower than those of GaN, Si and InGaAs transistors. The simulated μ_T values exhibits a good agreement with the analytical prediction given in Fig. 2(c2). Therefore, the plasmonic resonance is easier to be induced in the p-diamond TeraFET compared to other TeraFETs. This could be a huge advantage for p-diamond over other materials in making TeraFETs.

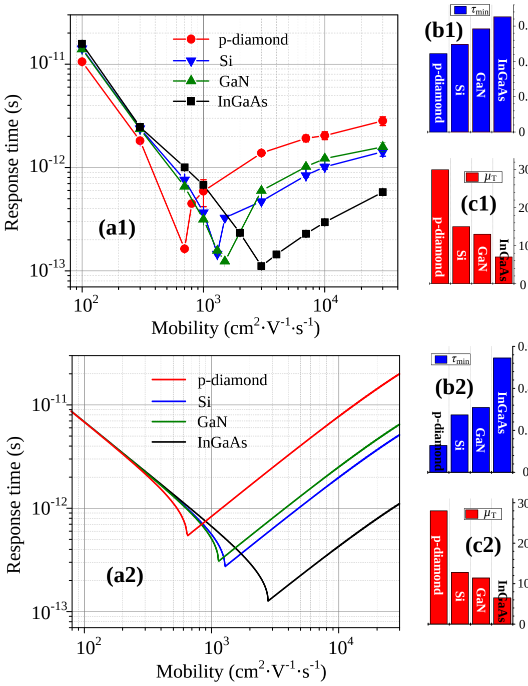

Fig. 1. Ultimate response times of TeraFETs as functions of mobility (a1), (a2), and their minimum response time (τ_r, in ps) (b1), (b2) and transition mobility (μ_T, in cm^2/Vs) (c1), (c2). (a1)-(c1) show the simulation data, and (a2)-(c2) present the analytical results. $U_0 = 0.1$ V, $L = 130$ nm, $T = 300$ K. The pulse width is 5×10^{-14} s.

To further evaluation the detection performance of TeraFETs, Fig. 2 illustrates the normalized DC voltage response versus gate bias for plasmonic TeraFETs at $T = 300$ K, $L = 130$ nm. Both analytical curves (solid lines) [2] and simulation values (symbols) are depicted in this figure. The analytical DC source-to-drain voltage response is proportional to the power of incoming AC small signal [6]:

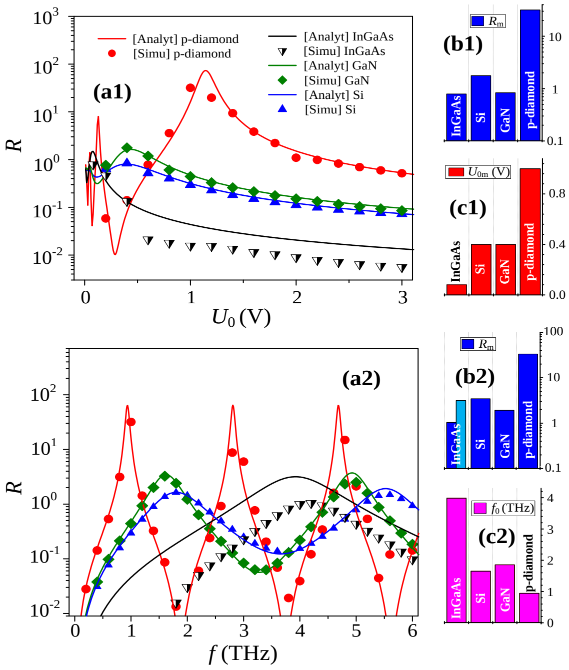

Fig. 2. Normalized response of different TeraFETs versus the gate bias U_0 (a1) and frequency f (a2), along with the amplitudes peak response (R_m) (b1), (b2), positions of peak response (c1), and the values of fundamental frequency ($f_0 = s/4L$, where $s = (eU_0/m)^{0.5}$ is the plasma velocity) (c2). The frequency and amplitude of incoming small signal in (a1) are set 1 THz. The gate voltage swing U_0 in (a2) is 1 V. The channel length L = 130 nm, under room temperate.

$$\frac{\mathrm{d}U}{U_0} = \frac{1}{4}\frac{U_{\mathrm{am}}^2}{U_0^2}\, f(\omega) \tag{2}$$

where U_{am} is the amplitude of incoming AC signal, $f(\omega)$ is a frequency dependent function given in [6], and is always positive. Besides, the normalization of dU is performed as $R = \mathrm{d}U\cdot U_0/U_{\mathrm{am}}^2$.

As shown in Fig. 2(a1) and Fig. 2(a2), at 300 K when the viscosity is relatively low, the simulation data show very good qualitative match with their corresponding analytical curves in all materials except InGaAs. The numerical differences are significant. The deviation between simulation and theory for InGaAs TeraFET is attributed to a much higher viscosity due to low effective mass ($m_{\mathrm{eff}} = 0.041m_0$). As seen from Fig. 2(b1) that p-diamond TeraFET has the largest peak response, and it leads all TeraFETs in response when U_0 is above 0.8 V. This indicates that p-diamond detectors might be most advantageous for high gate bias operation at room temperature. Fig. 2(a2) shows the normalized voltage response versus the driving frequency. In this case, p-diamond TeraFET has a much larger DC response than those of GaN, Si and InGaAs TeraFETs. At low frequency ($f < 1$ THz), the response of p-diamond TeraFET is the highest among all devices. This suggests that p-diamond detector might be the most suitable one for sub-THz detection, which is very important in technologies related to beyond-5G communications. Beyond 1 THz, the p-diamond TeraFET also yields the highest DC response in the vicinity of its harmonic peaks. Those features allow better performance for high-sensitivity detection in a wide dynamic and frequency range.

To explore the channel length dependence of TeraFETs, we also simulate the frequency dependence of normalized response at L = 20 nm, and the result is plotted in Fig 3. As seen, at a short channel condition, the "low f" region where p-diamond TeraFET has the highest voltage response expands to at least f = 6 THz. This should be attributed to the increase of fundamental resonant frequency $f_0 = s/4L$ as L decreases. Also, the amplitude of R in this case is negatively correlated to the effective massive of the detector material. Those results indicate that p-diamond TeraFETs may be more advantageous as high sensitivity detectors when the feature size of device is relatively low.

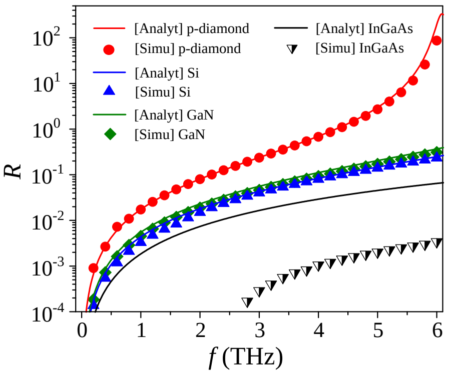

Fig. 3. Normalized response of the p-diamond TeraFET versus frequency under typical mobilities at the channel length of 20 nm. U_0 = 1 V, U_{am} = 5 mV, T = 300 K.

III. SUMMARY

The hydrodynamic simulation shows that the p-diamond TeraFET could enable resonant detection in below 1 THz band, thus promising for beyond 5G applications. Also, the p-diamond TeraFET have a high detection sensitivity in a large dynamic range, and the response characteristics can be adjusted by changing the gate length and tuning the gate bias.

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