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Injection Damage Analysis of pHEMT Low-Noise Amplifier Circuit under Electromagnetic Pulse

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ABSTRACT: Low-noise amplifier (LNA) is the most vulnerable device in the front-door coupling path of wireless communication link. When the electromagnetic pulse (EMP) is injected into the LNA circuit, it first generates the electromagnetic response with peripheral components, and then is transmitted further. This affects the pulse value transmitted to the internal semiconductor device and its degree of damage. The pseudomorphic high electron mobility transistor (pHEMT) type transistors are widely used in modern RF circuits because of their good stability and wide frequency characteristics. However, frequency-selective characteristics of a front-end system exacerbate the electromagnetic coupling damage of the LNA circuit in some frequency bands. Therefore, in this paper, vulnerable frequency points of the pHEMT LNA circuit under repetitive pulses are analyzed by injection experiment. It is found that both in-band and out-of-band lead to permanent damage to the LNA. For the more vulnerable 3 GHz frequency point, the electromagnetic response under injection withstand and absorption conditions was measured, determining that the gate external resistance offset follows a power-law relationship with the input power. Furthermore, the energy threshold was obtained, which assesses the energy that, after electromagnetic loss by an external 100 Ω resistor, is transmitted to the gate input and causes permanent damage to the LNA transistor. The breakdown damage mechanism of the gate-source of the LNA transistor is verified by failure analysis.

1. INTRODUCTION

Low noise amplifier (LNA) is the most vulnerable device in the front-door coupling channel of wireless communication link [1], which determines the degree of electromagnetic damage resistance of a communication system. When high-power microwave (HPM) is transmitted into a semiconductor device through an external circuit, the energy is distributed on the peripheral discrete components (e.g., resistors) and internal transistors of the device. Excessive power injected into the external circuit will change the resistance of peripheral components. This change regulates part of the signal energy absorbed by peripheral components and affects the pulse value transmitted to the transistor. When the value is too high, it will cause hot carrier effect in low noise amplifier (LNA) semiconductor devices. This effect causes instantaneous failure or permanent damage due to local breakdown inside the semiconductor device [2].

The core semiconductor devices of low noise amplifiers include various types, such as field effect transistor (FET), bipolar junction transistor (BJT), and pseudomorphic high electron mobility transistor (pHEMT) [3]. Among them, the pHEMT type is widely used in modern radio frequency (RF) circuits because of its good stability and broadband characteristics. However, the high electron mobility and material properties of pHEMT make them relatively sensitive to high-frequency electromagnetic waves and more susceptible to damage. Therefore, it is necessary to study the damage effect of pHEMT LNA under EMP injection.

The instantaneous failure of components is often caused by high-energy instantaneous shocks such as spike pulses. The focus of the research is to evaluate the relationship between LNA damage and pulse amplitude and frequency characteristics. Ref. [4] studied the thermal damage characteristics of GaAs pHEMT low noise amplifier under microwave pulse injection at 1.5 GHz. Ref. [5] studied the microwave damage effect of low noise amplifier of high electron mobility transistor under different drain voltage biases at 1 GHz, using TCAD simulation and experiment. Ref. [6] studied the nonlinear effects and attenuation characteristics of GaAs pHEMT LNA injected with HPM at 14.9 GHz in Ka-band at different amplitudes. Due to the technical limitations of microwave sources, it is often impossible to rise to the thermal damage temperature with a single pulse. The heat accumulation effect of repetitive pulses will continuously aggravate the temperature rise. The existing literature shows that under repeated pulse conditions, there is potential damage that is more serious than single pulse [7]. The focus of research on repetitive pulse damage is to evaluate the influence of energy density and pulse frequency on the thermal accumulation effect [8] and damage threshold parameters of LNA. Ref. [9] studied the physical mechanism of HPM-induced nonlinear effect in AlGaAs/InGaAs pHEMT LNA at 10 GHz. Refs. [10, 11] studied the nonlinear damage effect of low noise amplifier circuit under HPM injection at the L-band and C-band carrier frequencies of 6.6 GHz, demonstrating that nonlinear

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degradation is closely related to pulse characteristics. Ref. [12] studied the influence of pulse width and repetition frequency of L-band high power microwave on the damage threshold of low noise amplifier. Ref. [13] further demonstrated, through injection experiments, that under L-band conditions both the duty cycle and peak power of HPM significantly affect the gain of LNA. In summary, the study of the electromagnetic damage effects of pHEMT LNA with respect to parameters such as pulse amplitude and frequency is relatively in-depth. However, most of the research focuses on fixed in-band frequency points or narrow frequency bands. The frequency selection characteristics of the front-end system should ensure that low-noise amplifiers have vulnerable frequency points both within and outside of the wide frequency band.

Electromagnetic pulse does not directly affect an LNA transistor. Instead, it first passes through the peripheral circuit components and generates electromagnetic losses, and then passes to the input end of the core semiconductor device. Refs. [14, 15] studied the thermal failure mechanism of independent transistors under HPM repetitive pulses. However, in practical applications, transistors are generally not used independently. The impedance matching of the external circuit of the transistor electrode will have a direct impact on thermal failure. Ref. [16] studied the influence of external resistors connected to the transistor electrode on the electromagnetic damage effect of the device. It shows that the existence of resistance changes the damage process of the device. However, existing research has not yet analyzed the extent to which the injected energy is dissipated by vulnerable components along the signal transmission path, nor the impact that parameter variations of peripheral vulnerable components have on LNA circuit damage.

Thus, this paper studies the pulse damage mechanism of a pHEMT LNA circuit. In a wide frequency range, in-band and out-of-band vulnerable frequency points of the circuit are studied, and the response of external components under different pulses is studied. They aim to quantitatively evaluate the energy threshold of the transistor damage caused by transmission to the gate input end after electromagnetic loss of the peripheral signal circuit element. Furthermore, the study clarifies the relationship between the electromagnetic coupling of external resistors and the damage in the core circuit of the LNA.

The rest of this article is organized as follows. The second section of the paper explores the evaluation relationship between the pulse power loss of the external resistance and the LNA transistor damage threshold under the input condition. In the third section, based on the HPM pulse injection test platform, the in-band and out-of-band vulnerable frequency points of LNA under the action of repetitive pulses are analyzed. Furthermore, the relationship between the resistance drift of the peripheral signal circuit element and the power loss of the injected pulse is analyzed under the condition of the vulnerable pulse. The fourth section of the paper tests the thermal damage threshold of the LNA transistor corresponding to the change of interval time and, through microscopic injection failure analysis of damaged samples, verifies the correctness of the evaluation relationship and the theoretical analysis of LNA damage.

2. LNA TRANSISTOR DAMAGE AFFECTED BY POWER LOSS OF PERIPHERAL CIRCUIT UNDER HPM

2.1. The Damage Mechanism of High Energy Pulse Injection LNA Circuit

In a high-power environment, electromagnetic energy is injected into the device in the form of high amplitude and high energy density, resulting in power damage and thermal damage effects in local areas. The power damage is mainly because the pulse injection amplitude exceeds the tolerance threshold of the device material, resulting in a sharp increase in the local electric field, PN junction breakdown, and transistor structure failure. The pulse energy absorbed by the device has both heat production and diffusion consumption due to the combination of pulse duration and interval time. The energy damage depends on the energy accumulation caused by long pulse duration, high pulse number, and repetition frequency, so that the local heat cannot be effectively dissipated in a short time, resulting in thermal burning of the material. From heat conduction equation, the classical relationship between pulse input power and pulse width can be expressed as

$$P = K_0 \cdot \tau^{-1/2} \tag{1}$$

where $K_0 = A\sqrt{\pi K \rho C_p} \cdot \Delta T$ represents the ability of the material to conduct heat. K, ρ, C_p, ΔT, and A represent the thermal conductivity, material density, specific heat capacity, temperature rise, and device cross-sectional area, respectively, while τ denotes the pulse width.

Different pulse widths τ will produce different damage effects. This paper focuses on the electromagnetic pulse in the range of $100\,\text{ns} < \tau < 1\,\text{ms}$. At this time, the influence of input power change on the burn-out threshold exceeds the influence of pulse width change. The corresponding damage power and energy threshold formula are

$$P = B\tau^{-1/2} \tag{2}$$

$$E = B\tau^{1/2} \tag{3}$$

where coefficient B reflects the combined effect of thermal diffusion and material heat capacity on the internal temperature rise of the device.

2.2. Electromagnetic Loss Calculation of Gate External Resistance

Under the action of electromagnetic pulse, HPM first enters the LNA circuit along the transmission path, so that the peripheral matching circuit is first subjected to electromagnetic impact. The external matching of pHEMT transistors is classically in the form of a common source. Z_1 and Z_2 are usually composed of transmission lines and discrete components (resistors, capacitors, etc.), which jointly regulate the input matching network N_1 of the LNA transistor gate. The load matching network N_2 connected to the drain is mainly used to achieve output impedance matching and resonance tuning. The source level is connected to the negative feedback network N_3 to ensure the stability of the circuit, as shown in Fig. 1.

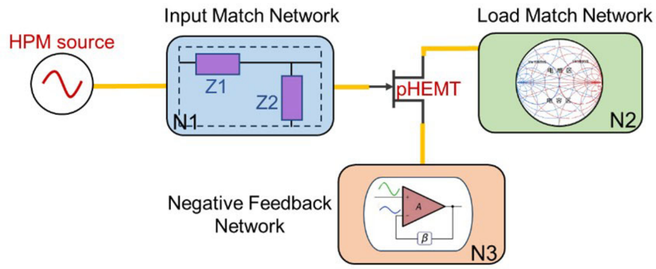

FIGURE 1. The gate external input matching circuit.

The input matching network affects the electromagnetic response and power transmission of LNA at different frequencies. The frequency selection characteristic makes it easy to damage the LNA under high power pulse injection in the band. At the same time, the decrease of the suppression ability near the cutoff frequency or in the parasitic passband will also cause LNA damage outside the band.

However, when the electromagnetic pulse is transmitted through the matching network to the transistor gate, it will cause significant power dissipation in the network, and the loss is mainly concentrated on the resistance element. High power injection makes the resistance withstand a strong pulse current in a short period of time; temperature rise will lead to abnormal heat generation of the component; thermal imbalance will cause resistance drift. Therefore, under the most vulnerable frequency condition, after experiencing resistance drift loss through the gate-connected external resistor, the damage impact transmitted to the transistor is the most severe, which is the evaluation focus of the damage effect research.

The initialized resistance offset percentage (ΔR) increases with the increase of input power, described as

$$\Delta R = \left(\frac{R_1}{R_0} - 1\right) \times 100\% \tag{4}$$

where R_0 and R_1 are the corresponding resistance values before and after HPM acts on the resistance, respectively.

Resistance drift causes electromagnetic losses of varying degrees, resulting in dynamic changes in the power loss on the resistor, with a small resistance offset under small signal conditions. According to Joule's law, the power loss corresponding to the change in the resistance value of the signal circuits peripheral to the gate of the LNA transistor under different input powers is

$$\Delta P_{\text{loss}} = P'_{\text{loss}} - P_{\text{loss}} = P_{\text{in}} \cdot \frac{R_1 - R_0}{R_0 + R_L} = P_{\text{in}} \cdot \frac{\Delta R}{1 + \frac{R_L}{R_0}} \tag{5}$$

where P_{in} is the input peak power (dBm) at the signal input of the LNA circuit; P_{loss} and P'_{loss} are the loss power on the resistor before and after the resistance shift, respectively; R_L is the equivalent load resistance.

Then, the power threshold that is transmitted to the gate input after dynamic electromagnetic loss through the peripheral resistor and causes damage to the transistor is

$$P = B\tau^{-1/2} = P_{\text{in}} - P'_{\text{loss}} \tag{6}$$

In the case of repetitive pulses, if the pulse interval is too small, the heat acting on the LNA cannot be dissipated in time, which will cause a thermal accumulation effect, resulting in an increase in the temperature of the LNA, which will lead to thermal damage of the device. f_{PRF} is the pulse repetition frequency. When the number of pulses N is greater than 1, the total time occupied by i pulses is i/f_{PRF}. Then, the contribution of a single pulse over the entire time period is expressed as $\frac{\tau}{i/f_{PRF}}$. Ref. [17] shows that, as the number of pulses increases, the rate of increase in pulse width τ gradually decreases. The thermal accumulation effect between pulses can be expressed by introducing a logarithmic correction factor $\ln[1 + \frac{\tau}{(i/f_{PRF})}]$. The corrected contributions of all pulses are summed up with Σ to obtain the total thermal cumulative effect after N cycles. The thermal cumulative effect causes changes in the thermal conductivity and heat dissipation efficiency of the material, resulting in a nonlinear increase in temperature.

Multiplying Eq. (3) by a correction factor and accumulating and normalizing all the pulses, the equation for the energy threshold that is injected into the input of the transistor and results in damage after electromagnetic loss through the gate external resistor is deduced to be

$$E = \frac{B\tau^{1/2}}{N} \sum_{i=1}^{N-1} \ln\left(1 + \frac{\tau}{i/f_{PRF}}\right) \tag{7}$$

where $1/N$ is the normalization factor. It shows that the energy damage process consists of the interaction of parameters such as pulse amplitude, pulse width, number of pulses, and pulse repetition frequency.

2.3. Theoretical Analysis of Electromagnetic Damage in Core Semiconductor Devices

When electromagnetic energy propagates through the peripheral signal transmission circuit to the internal core devices (such as transistors), the energy is concentrated near the transistors and other key components, resulting in sharp localized electric field changes and microscopic thermal shocks. Since the first stage transistor of the low noise amplifier receives signals directly and is not buffered, it is susceptible to overheating and breakdown caused by the electromagnetic pulse. Therefore, its electromagnetic damage is usually caused by the first stage.

In order to investigate the dynamic electromagnetic damage response of the transistor under different injected power shocks and the influence of peripheral circuits, a pHEMT LNA circuit is constructed and simulated. The classical application circuit is shown in Fig. 2, which generally contains two to three levels of pHEMT transistors and is biased by a 5 V DC power supply. According to the first-stage transistor electrode current variation with the injected power (as shown in Fig. 3), it shows that the damage of the low noise amplifier under the action of HPM gradually increases with the increase of the pulse amplitude. The gate-source currents gradually equalized, indicating that avalanche breakdown occurs at the gate bias toward the source, and a low-impedance path between the gate and the source appears.

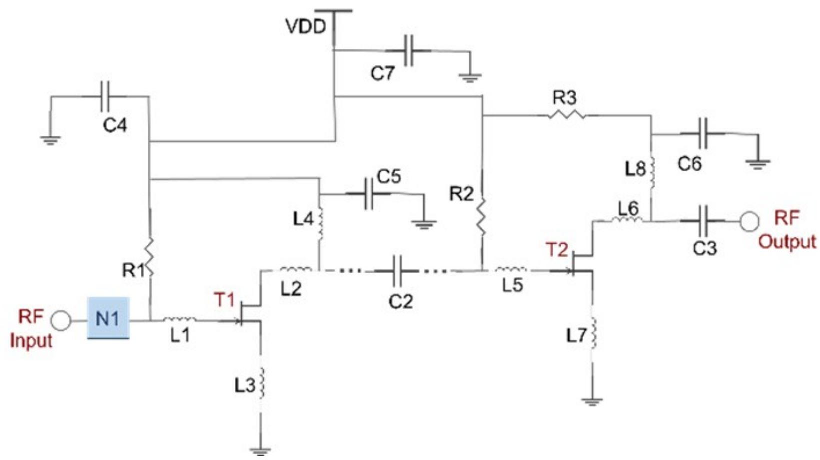

FIGURE 2. Application circuit for pHEMT chip.

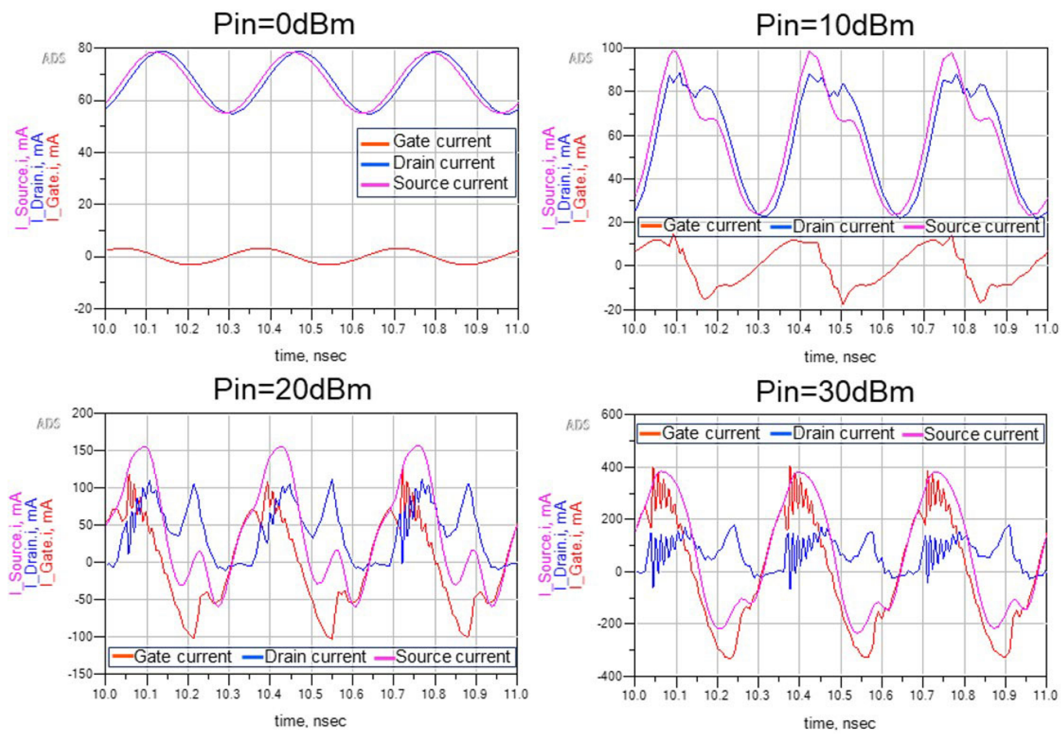

FIGURE 3. Variation of electrode current for the first stage of pHEMT at different injection powers.

3. REPEAT THE POWER LOSS OF THE GATE EXTERNAL RESISTOR AT THE VULNERABLE FREQUENCY POINT UNDER HPM INJECTION

3.1. Experimental Setup for Injecting the DUT

The HPM pulse injection experimental platform is shown in Fig. 4, which is mainly used to realize the real-time monitoring of low-noise amplifier gain. The specific configurations are: signal source generator, power amplifier, circulator (isolator), coupler, parts to be tested, attenuator, DC power supply, and network analyzer. The LNA to be tested for the experiment is kept in normal power-on operation with an in-band frequency band of 0.1 GHz to 6 GHz [18].

The network analyzer was synchronized to provide a small signal to the circuit. Its port 1 is connected to the coupling end of coupler 1 through circulator 2, and port 2 is connected to the coupling end of coupler 2, so as to monitor the gain of low noise amplifier in real time and collect data. The signal strength at the coupling end is attenuated by 20 dB. The circulator is used to prevent high power reflection shocks from exceeding the instrument safety margins. All instruments in the test rig except the circulator have a passband range above 12 GHz.

A typical waveform of the sinusoidally modulated HPM generated by the ARB Toolbox and subsequently produced by the signal generator is shown in Fig. 5. The number of pulses is ten. It has a pulse width of 100 μs, a rise and fall time of 10 μs,

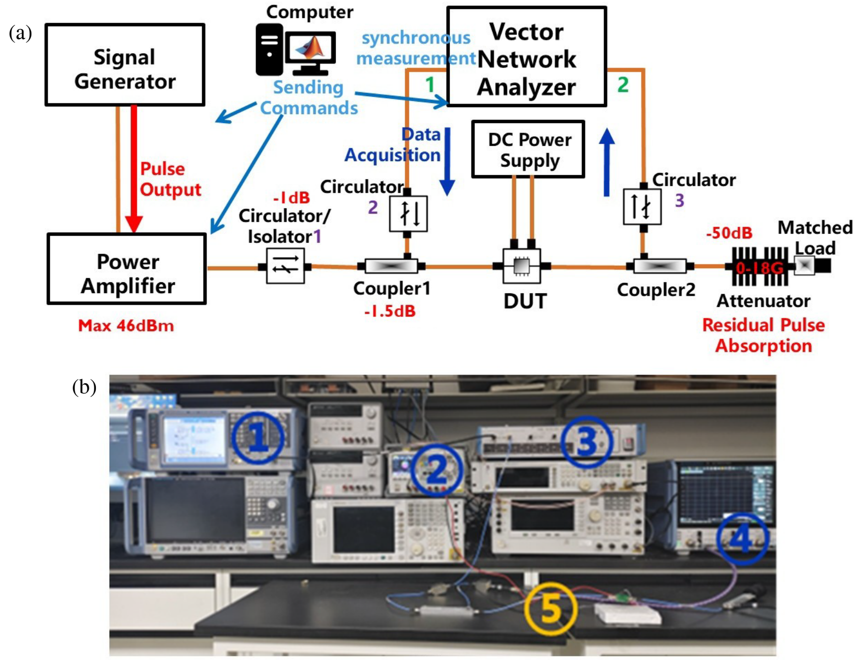

FIGURE 4. Test platform construction. (a) System block diagram. (b) Measured connection.

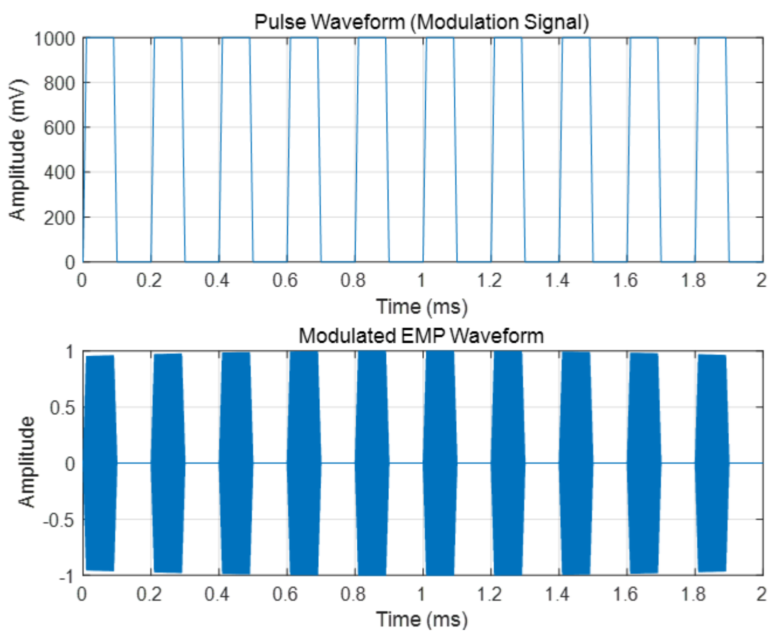

FIGURE 5. The typical waveform of HPM injection with a pulse width of 100 µs.

and a total period of 3 ms. Fig. 6 shows that LNA circuit electromagnetic coupling damage test relationship under repetitive pulse.

It is worth mentioning that when the injected HPM pulse causes severe damage to the core transistors in the LNA circuit, the gain value decreases significantly, and the signal is completely blocked. Therefore, the permanent damage to the LNA under test can be determined by observing that S_{21} parameter is less than -15 dB after being subjected to a strong electromagnetic pulse.

3.2. The Frequency Sensitivity of pHEMT LNA

In order to better compare the changes in the S_{21} curves before and after the damage and to determine the typical frequency points within (1 GHz, 12 GHz), the signal generator was turned on at 1 s. The initial pulse power generated by the signal generator is set to -79 dBm, which corresponds to the peak power of the pulse to be -0.61 dBm after amplification by the power amplifier and injection into the input of the LNA circuit through the coupler. Fig. 7 shows that under the same injection pulse condition, the LNA damage thresholds corresponding to differ-

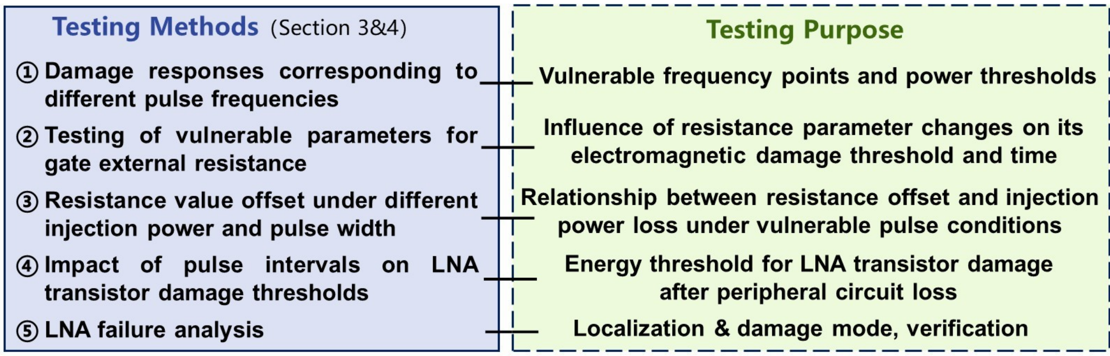

FIGURE 6. Low noise amplifier circuit electromagnetic coupling damage test relationship

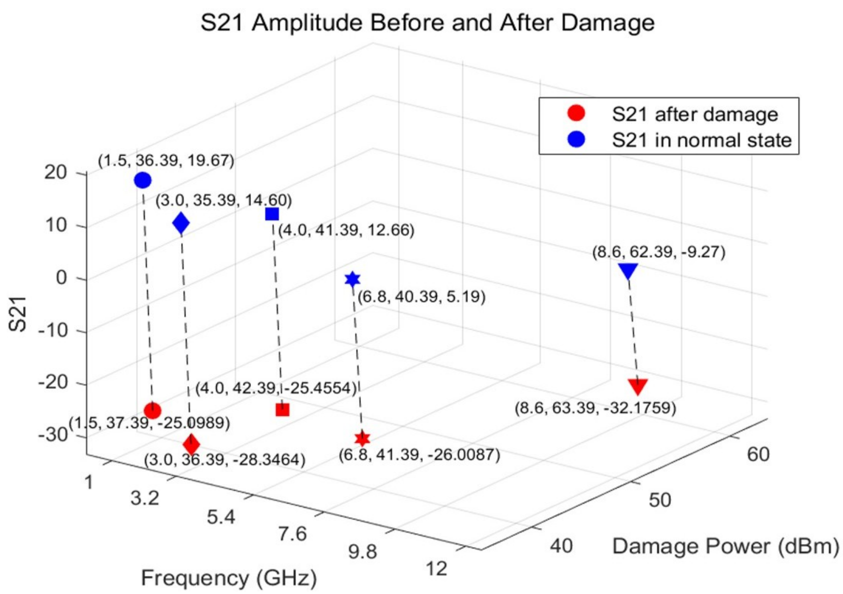

FIGURE 7. Vulnerable frequency points and damage power inside and outside the band.

ent vulnerable frequency points are not exactly the same. The credibility of the vulnerable frequency points and their corresponding damage power thresholds was verified through repeated experiments. Take 3 GHz as an example (Table 1).

TABLE 1. Repeated experiments of vulnerable frequency points.

Condition setting	Vulnerable points	Damage power
Fix: step 0.2 GHz, increase	3 GHz	36.39 dBm
Fix: step 0.2 GHz, decrease	3 GHz	36.39 dBm
Random: step 0.2 GHz	3 GHz	36.89 dBm

For the in-band (1 GHz, 6 GHz) band, when the input peak power of LNA circuit increases to 36.39 dBm, 37.39 dBm, and 42.39 dBm respectively, the corresponding S_{21} curve drops below -20 dB at 3 GHz, 1.5 GHz, and 4 GHz. Permanent damage occurs to the corresponding LNA. It is shown that when the input power increases, the LNA transistor energy absorption increases due to the high gain of the in-band frequency point near the center frequency point. With the rapid rise of temperature, the 2DEG mobility is more affected, which accelerates the energy damage process. At in-band frequencies away from the center frequency, the performance of the LNA itself degrades. When the input power increases, due to factors such as impedance mismatch, more energy will generate additional losses in the LNA circuit in the form of reflection, resulting in local overheating of the components and energy damage.

When the injection peak power of the LNA circuit input continues to increase to 41.39 dBm and 63.39 dBm, the measured LNA undergoes permanent damage at 6.8 GHz and 8.6 GHz. It shows that although the frequency selectivity of the device has an inhibitory effect on the signal, some energy will still be coupled into the LNA circuit at high power. This extra energy will generate stray current inside the LNA, interfere with the normal circuit work, and generate heat. Long-term accumulation can also cause permanent damage to LNA. The mechanism of out-of-band damage is similar to that of in-band frequency, but the degree of energy damage is different.

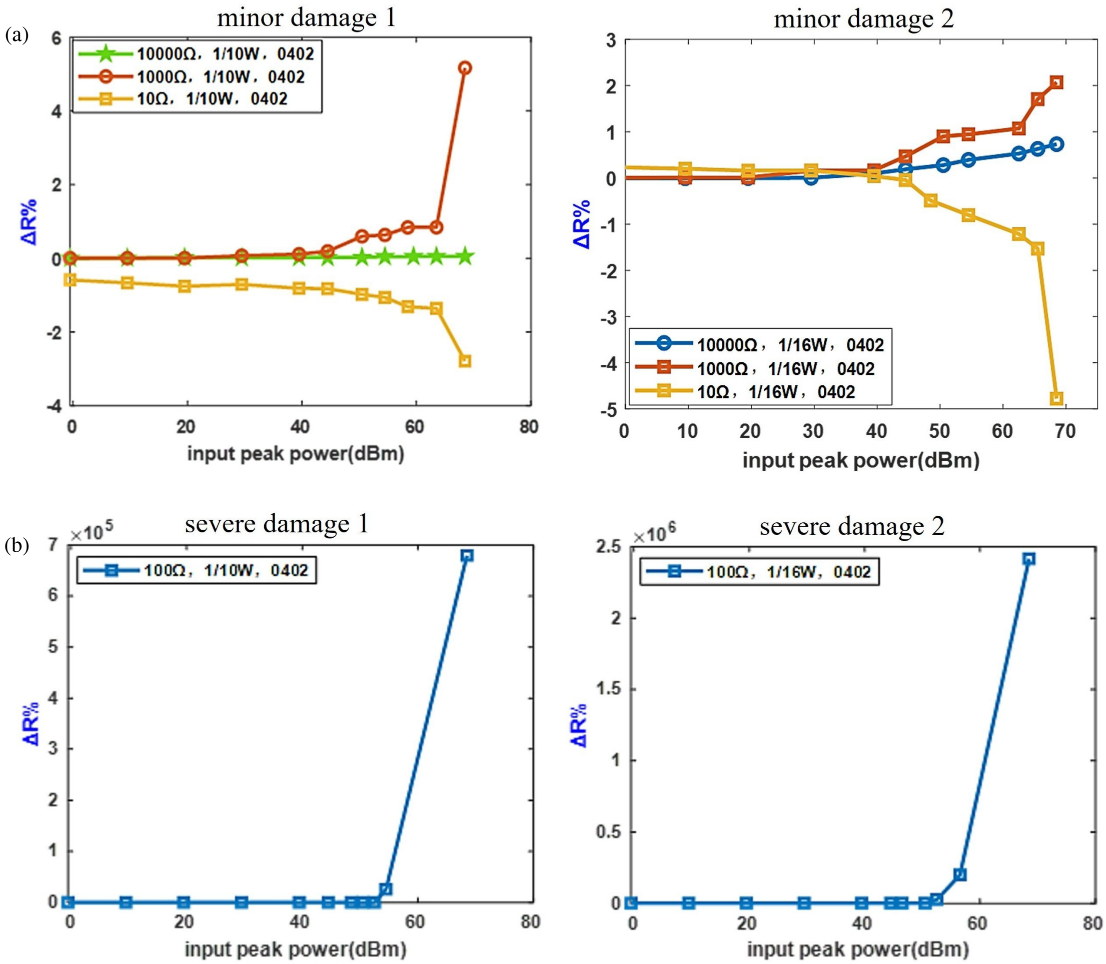

FIGURE 8. The effect of resistance on resistance damage under different input power. (a) Minor damage. (b) Serious damage.

3.3. The Relationship between the Resistance Offset of the External Resistor and the Heat Absorption of the Injected Pulse at 3 GHz

3.3.1. The Relationship between Different Damage Factors and Electromagnetic Coupling Damage of Gate External Resistance

From Subsection 3.2, it is clear that the transistor is susceptible to damage at 3 GHz. In order to clarify the gate input conditions that cause the transistor to be most vulnerable at vulnerable frequency points, it is necessary to evaluate the degree of electromagnetic loss of the gate external resistor at 3 GHz for different damage conditions. The tolerance and heat absorption-heat dissipation capability of the external resistor changes depending on the resistance value, power rating, and size. Thus, they exhibit different injection damage effects for high power pulses. The wider the pulse width is, the more obvious the damage effect is. The damage level of the peripheral resistor is analyzed for a repetitive pulse with a pulse width of 100 μs.

Figure 8 shows that under repetitive pulses conditions, the damage degree of the external resistor increases with the increase of the input power, which is basically reflected in the power-law function relationship. The reason for this phenomenon is temperature rise effect. The increase of pulse power will cause the temperature of the component to rise, resulting in more serious resistance damage. The temperature rise is not always positively correlated with input power, as the offset curve corresponding to the resistance value of 10 Ω. Although it belongs to the same manufacturer and type as other resistance values, the overall trend is negatively correlated with the input power. The degree of resistance damage does not continue to increase with the increase of resistance. When the resistance is close to the saturation value, the absorbed energy is not enough to cause serious thermal damage due to the limited current and low energy transfer efficiency.

Figure 8(b) shows that when the rated power is $1/10$ W and the resistance 100 Ω, the resistance has a damage effect at the peak power of 50.5 dBm, and serious damage occurs when the damage power threshold is 52.5 dBm. At $1/16$ W rated power, the power threshold for permanent damage at 100 Ω is 50.5 dBm. It shows that under the same injection condition, the reduced rated power accelerates the damage process of the resistance and reduces the damage power tolerance of the resistance.

Large package size usually means that the tightness of the internal arrangement is alleviated, and the heat dissipation space is improved. It generally has a larger rated voltage. Compared

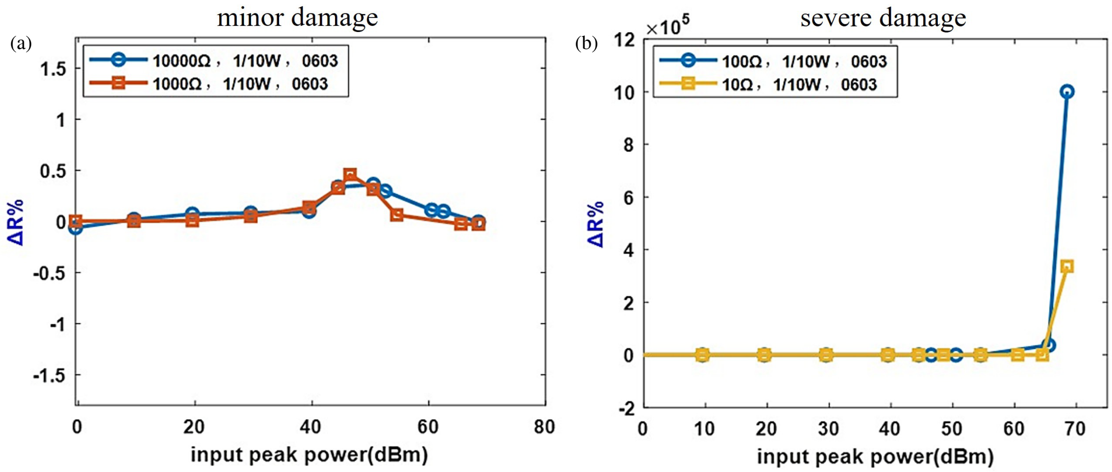

FIGURE 9. The size of the package under different input power on the resistance damage. (a) Minor damage. (b) Serious damage.

with Fig. 8(a), the percentage of the initial resistance offset caused by input power in Fig. 9(a) increases first and decreases as input power increases when the resistance is 10 kΩ and 1 kΩ. This is because when the input power is low, the metal oxide material in the resistance will weaken the electron mobility as the temperature rises, resulting in an increase in the resistance. When the power is further increased, the continuous temperature rise will cause the structural change of the material, so that the resistance state caused by the temperature rise is changed.

Figure 9(b) shows that the increase of package size accelerates the damage process of 10 Ω resistor. Permanent damage occurs at a peak power of 68.5 dBm, and the damage power of the 100 Ω resistor is increased to 54.5 dBm. It explains that under the same injection conditions, the package size affects the heat dissipation capacity and changes the resistance electromagnetic coupling damage threshold.

In summary, the resistance, rated power and size caused by the resistance of the external resistance tolerance and heat absorption-heat dissipation capacity changes will affect the resistance under the same conditions of the damage threshold. The impact of HPM damage is the most serious when the resistance is 100 Ω.

3.3.2. Electromagnetic Loss of Peripheral Signal Circuit Resistance under Different Injection Conditions

At 3 GHz & 100 Ω, the resistor produces two distinct damage effects, namely degradation and full damage, as the input power increases. This is reflected in the percentage shift in the initialized resistance value corresponding to the resistor, as shown on the left side of Fig. 10. The overall decrease in damage power threshold corresponding to an increase in pulse width from 100 ns to 100 μs is found. The right side of the figure shows resistance values of the resistor after the high power microwave pulse with an average power of 33 dBm is injected at the input end under different pulse widths, and it shows that a larger the pulse width corresponds to a larger damage impedance value.

Therefore, the initialized resistance offset percentage (ΔR) gradually increases as the input power increases. An increase in

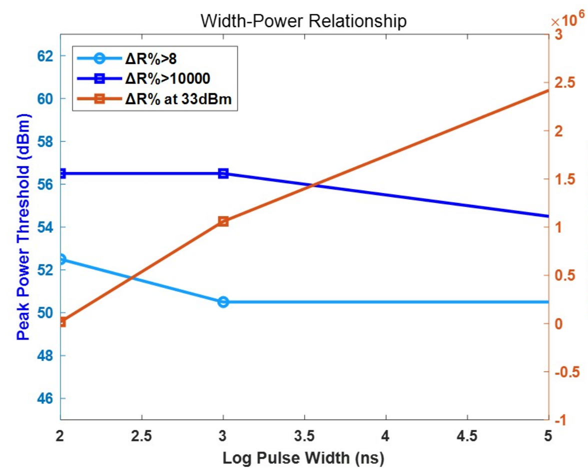

FIGURE 10. The relationship between the damage threshold power and resistance shift with the pulse width.

the injection pulse width results in a consequent increase in the damage power of the resistor. This indicates that the three parameters interact with each other. However, comparing Fig. 7 with Fig. 8, when the carrier frequency is 3 GHz and the pulse width 100 μs, the input power required for the LNA transistor to undergo permanent damage is less than the slight damage power of the external resistor of 100 Ω @ $1/16$ W. It shows that the effect of pulse width on power loss can be simplified, and the offset is small ($\Delta R \ll R_0 + R_L$). Therefore, the power law functional form establishes the relationship between the percentage offset of the resistance value of the 100 Ω external resistor and the power loss as

$$\Delta R = C \cdot \left(P_{\text{in}}\right)^{\alpha} = 0.0002 \cdot \left(P_{\text{in}}\right)^{1.7489} \tag{8}$$

$$R^2 = 0.9922 \tag{9}$$

where C denotes the damage accumulation per unit input. Substituting Eq. (8) into Eq. (5), the resistance power loss of the actual LNA transistor gate peripheral signal circuit corresponding

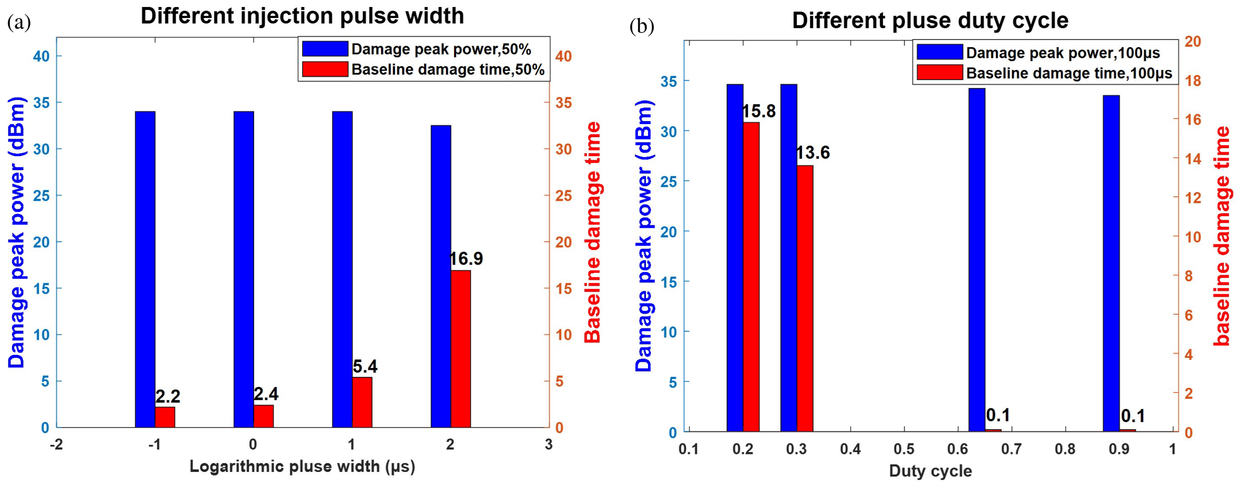

FIGURE 11. The relationship between device damage and pulse width and duty cycle at 3 GHz. (a) Change with pulse width. (b) Change with duty cycle.

to different input powers is

$$P'_{\text{loss}} = (\Delta R+1)\cdot P_{\text{loss}} = \left(1+0.0002\cdot(P_{\text{in}})^{1.7489}\right)\cdot P_{\text{loss}} \quad (10)$$

4. PERMANENT DAMAGE THRESHOLD AND FAILURE VERIFICATION OF LNA TRANSISTOR UNDER REPEATED HPM INJECTION.

4.1. LNA Transistor Damage Energy Threshold after Peripheral Circuit Loss

In the case of repetitive pulses, the temperature variation of thermal damage is affected by the pulse interval time. The interval time determines the ratio of thermal accumulation to thermal dissipation in the device and is influenced by the pulse width and duty cycle. The pulse width directly determines the duration of individual pulse energy injection, and the duty cycle affects the average energy injection of the pulsed signal.

The smallest moment at which the damage was captured was used as the reference point. Repeated pulses with the same pulse amplitude and 50% duty cycle were injected into the LNA circuit. At the carrier frequency of 3 GHz, adjust the pulse width in decade (ten-fold) steps from 100 ns up to 100 µs. Fig. 11(a) shows that the LNA transistor is most susceptible to damage when the pulse width is 100 µs, and the damage law caused by pulse width is also applicable within the frequency band. It shows that a larger pulse width means that the energy is injected into the device for a longer time at the same power. The increased heat generation in the pHEMT channel during a single pulse makes the internal temperature of the device rise more significantly. It also accelerates the thermal destruction of the lattice structure and affects the mobility of the two-dimensional electron gas (2DEG), which results in a change in the LNA damage process. Fig. 11(b) shows that with a single pulse period of 220 µs, as the repetition pulse duty cycle gradually decreases from 0.9 to 0.2, the damage effect time of the corresponding LNA transistor is prolonged at 3 GHz, and the damage power threshold is relatively increased. It shows that in the same period, the smaller duty cycle will make the pulse width narrower and the pulse interval longer. The decrease of pulse width will shorten the heat generation process at the same time, while the growth of pulse interval will speed up the heat dissipation process simultaneously. This makes the heat accumulation in the device during the cycle is not enough to cause damage, thus the damage time of the device is prolonged.

When the LNA transistor is permanently damaged, the device is in the (1 GHz, 12 GHz) frequency band which is calculated by Eq. (7). Under the condition of pulse width, the relationship between the damage energy threshold and the injection of ten HPM signals is

$$E = \frac{\left(-24.13\,\tau + 0.00086\right)\cdot \tau^{1/2}}{N} \sum_{i=1}^{N-1} \ln\left(1+\frac{\tau}{i/f_{\text{PRF}}}\right) \quad (11)$$

$$R^2 = 0.998 \quad (12)$$

where the coefficients B are fitted using least squares to improve accuracy.

4.2. Intuitive Injection Failure Analysis

After the electromagnetic pulse is transmitted to the LNA transistor through the gate, it will further act on the internal structure. The damaged samples were observed by decapsulation (Decap), which did not show any obvious abnormalities in Fig. 12. This indicates that the transistor damage occurred in the internal (microscopic) structure. In order to further analyze the specific reasons for the permanent damage of the low noise amplifier caused by high power microwave, this section will use a more intuitive approach to perform failure localization on the decapped damaged LNA samples and clarify the failure modes.

Apply DC voltage and inject a signal into the chip after Decap to simulate the chip's operating environment. Comparing the injection I-V curves of intact samples and damaged samples

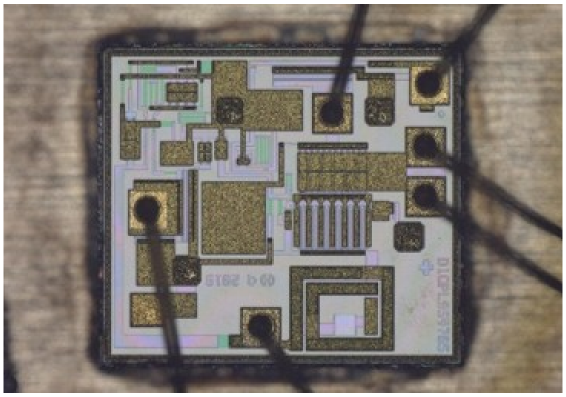

FIGURE 12. Decapsulation examination.

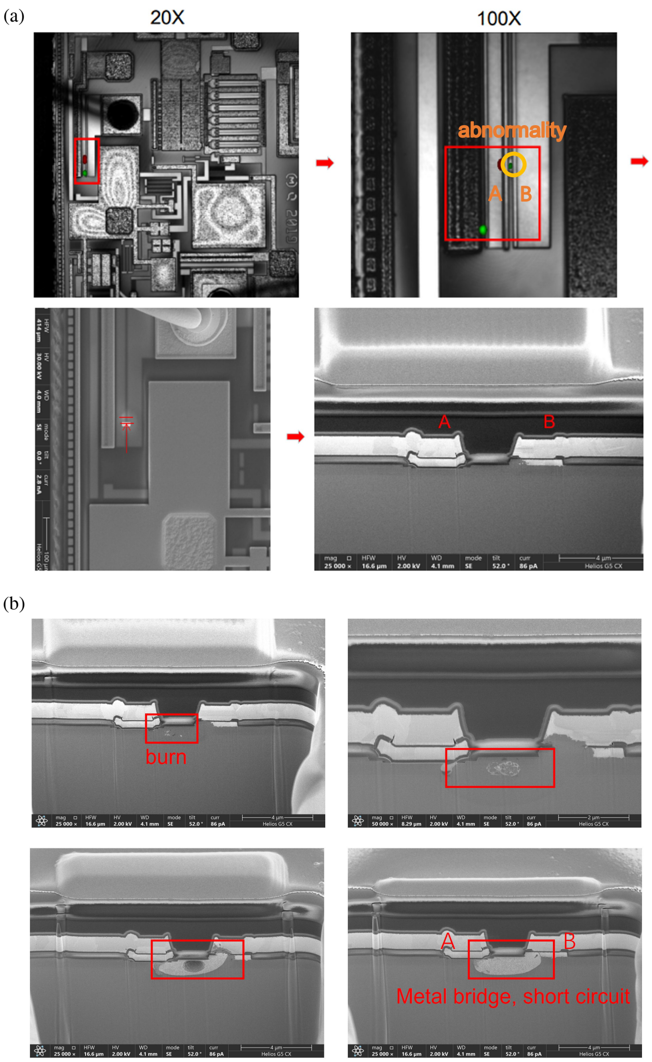

FIGURE 13. LNA abnormal bright spot failure analysis. (a) Slice angle of abnormal position of failure highlight. (b) Deep propulsion process.

reveals that the pin2-epad of the damaged sample has a large current passing through the origin and tending to the Y axis at a small voltage. The parameters were PIN2-GND-10 mV–1.9 mA. It shows that a short circuit phenomenon has occurred.

In order to clarify the failure position, the difference position of the IV curve is selected, and the optical beam induced resistance change (OBIRCH) test is carried out under limited voltage and current. The chip presents abnormal luminous spots due to the impedance change at the abnormal location. The location of the bright spot is shown in Fig. 13(a). Obvious abnormalities are found in the locations of A and B metal lines, and there are obvious abnormal white pits on the surface of the yellow circle location (for the change of metal color after burn-in). However, there are many reasons for the generation of bright spots, mainly junction avalanche breakdown, substrate defects, latch-up effects, etc. To further clarify the specific failure model, the internal morphology of the failed sample chip needs to be observed. For the GaAs process, the focused ion beam (FIB) slicing method is used.

Positional slicing was performed on the location of the highlight anomaly, and the angle of slicing is marked in the figure. Anomalies were found during the depth advancement of the sliced location, as shown in Fig. 13(b). Burning was observed on the two metal lines A and B (at the gate and source). The middle metal line at the arrow position showed metal bridging resulting in a short circuit in the chip.

5. CONCLUSION

This paper built the frequency domain automatic injection test platform. It is found that under repeated HPM conditions, there are frequency points leading to permanent damage of LNA in and out of the band. Based on the corresponding damage power, the 3 GHz frequency point is selected for the LNA circuit damage threshold analysis. The results show that the electromagnetic pulse acting on the external resistance of the gate will cause the resistance value to drift. The change of damage factors such as heat production, heat dissipation, and withstand value will cause the change of thermal effect and failure tolerance limit, which will all affect the degree of resistance value to drift. The resistance drift of the gate external resistance has a power-law relationship with the input power, while the 100 Ω resistor is most severely impacted. For LNA circuits, reducing the pulse width and duty cycle under the same injection conditions will slow down the damage process of LNA circuits. The power loss of the external resistor affects the energy threshold at which pulse width induces device permanent damage. In addition, the failure analysis shows that the permanent damage of the LNA circuit caused by high power microwave is due to the breakdown of the channel between the gate and the source in the pHEMT transistor.

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