Effect of negative resistance in the noise behavior of Ka Band IMPATT diodes.

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Abstract

Noise properties and performance of DDR IMPATT diode at *Ka Band* frequency has been investigated through modeling and simulation technique. An iterative method has been used to study the small signal negative resistance properties and it's effect on the noise performance of the device. Negative resistance of Si and others compound semiconductor based IMPATT (like GaAs, SiC, InP, GaN) has been found by this simulation technique. It is obtained that 3C SiC has maximum negative resistance value of 8.70 ohm at a dc bias current density of 3.5×10^7amp/m^2 at a frequency of 33 GHz. It is also obtained that 3C SiC has the minimum noise measure value at Ka band. Others avalanche noise parameters like shot noise ratio, noise spectral density have been calculated along with the effects of parasitic series resistance and temperature on the device's noise performance. It is also observed that noise measure of the device is increased with increasing parasitic series resistance and noise measure is decreased with increasing temperature. It is obtained that 3C SiC has the noise measure value 58.64 dB at 500K. Results of the analysis presented in this paper will be useful to realize a comparative study of noise performance of different semiconductor based IMPATTs for Ka band frequencies.

Keywords: Noise in IMPATT, Ka band IMPATT, negative resistance characteristics, Avalanche noise at Ka Band, Noise simulation of DDR IMPATTs.

1. Introduction

The IMPact Avalanche ionization Transit Time (IMPATT) diodes are emerged as a most powerful solid state sources operating in the microwave and mm wave frequencies. The one of the main drawbacks of this type of diode is its noisy [Sze (1981)] characteristics. This paper presents a general theory of avalanche noise [Gummel (1967), Reidarl (1976), Bernad (1962), Hermann (1971)] that starts from basic assumptions. A noise analysis model is developed to compare the noise characteristics of Si and others compound semiconductor based IMPATT (like GaAs, SiC, InP, GaN). DDR structures of these IMPATT are analyzed. The negative resistance has the crucial role on noise performance of IMPATT. A computer based iterative method is presented in this paper to estimate the avalanche noise characteristics of IMPATT diode. This method is applicable with an arbitrary doping profile and realistic ionization co-efficient. Authors have applied a simulation technique to Si and others compound semiconductors like GaAs, InP, SiC, GaN to fabricate IMPATT. Noise measure and others noise parameters like shot noise ratio and noise spectral density have been calculated and a comparison of noise performances is made based on these parameters for Ka-band IMPATT diode.

2. Simulation Methodology

The devices were designed following an IMPATT mode DC simulation scheme. High frequency properties of the diodes were then computed by simulation technique. The microwave properties such as total negative resistance (-R), susceptance (B), power output from the device were determined from the solution. The negative resistance characteristic is vital for noise analysis of the device. The different noise parameters such as noise measure, shot noise ratio, open circuit noise voltage were computed. Initially Si based IMPATT structure is chosen for noise analysis, later different compound semiconductors like InP, GaAs, SiC, GaN based IMPATTs. In figure 1.1 a DDR structure [A. Acharyya (2011)] of IMPATT is shown. W is the total width of the depletion layer. x_o is the position of the junction. D.C analysis of the DDR structure was carried out by solving Poission's equation [A. Acharyya (2010)] including mobile space charge in the depletion layer of the diode.

Poission's equation is given as,

$$dE/dx=(N_D-Na+p(x)-n(x)) \quad (1)$$

Then small signal analysis is carried out by solving the following second order differential equation.

$$d^2R/dx^2 + (\alpha_n- \alpha_p).dR/dx - 2.r_n.(\omega/v`).dX/dx + ( \omega/v`^{2}-H).R-2.\alpha`.(\omega/v`).X - 2.\alpha`/(v`.\varepsilon) = 0 \quad (2)$$

and $$d^2X/dx^2 + (\alpha_n- \alpha_p).dR/dx - 2.rn.(\omega/v`).dR/dx + ( \omega/v`^{2}-H).X-2.\alpha`.(\omega/v`).R + \omega /(v`^{2}.\varepsilon) = 0 \quad (3)$$

where R, X are the resistance and reactance values, $\alpha_{n,}$ α_p ionization coefficients and H is a function of electric field.

The boundary conditions [A. Acharyya (2010)] are given by the following equations:

at, x = 0,

$$(\delta R/ \delta x) + (\omega X/ v_{ns}) = -1/ (v_{ns}.\varepsilon) \quad (4.a)$$

$$(\delta X/ \delta x) – (\omega R/ v_{ns}) = 0 \quad (4.b)$$

at, x = W,

$$(\delta R/ \delta x) - (\omega X/ v_{ps}) = 1/ (v_{ps}.\varepsilon) \quad (4.c)$$

$$(\delta X/ \delta x) + (\omega R/ v_{ps}) = 0 \quad (4.d)$$

Where, $v` = (v_{ns}.v_{ps})^{1/2}$ , $\alpha` = (\alpha_n. v_{ns} + \alpha_p. v_{ps})/(2. v`)$, $r_n = (v_{ns} - v_{ps})/ (2. v`)$.

This is further proved by plotting G-B plot for different optimized compound semiconductor structures based IMPATTs .The RF power output PRF[Panda (2009)] from the device can be obtained and can be expressed as:

$$P_{RF} = V_{RF.}{}^{2}(-G).A/2 \quad (5)$$

Where, V_{RF} is the amplitude of the RF swing. $V_{RF} = V_B/2$ is considered for 50% modulation index value. A is the area of the diode and –G is the negative conductance [A. Acharyya (2011) of the diode. Thus G-B plot represents the estimation of power generation of the device and stability through quality factor Q=B/G.

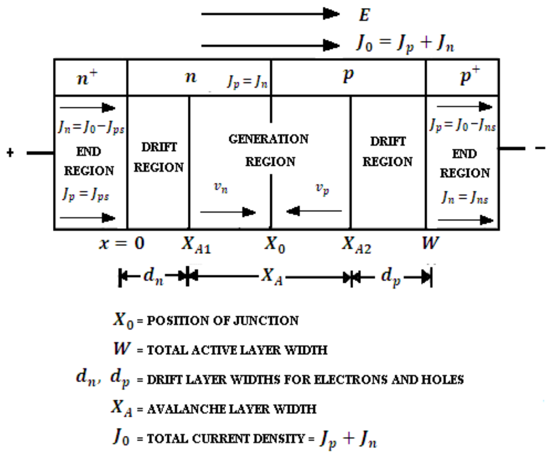

Fig. 1 The Active Layers of a Reverse Biased p-n junction.

3. Result and Discussions:

The G-B plot of a Si based IMPATT is shown for the different dc bias current density .It is seen from the figure that maximum negative conductance is obtained at the bias current density $2.5\text{x}10^8$ Amp/m^2 at Ka band.

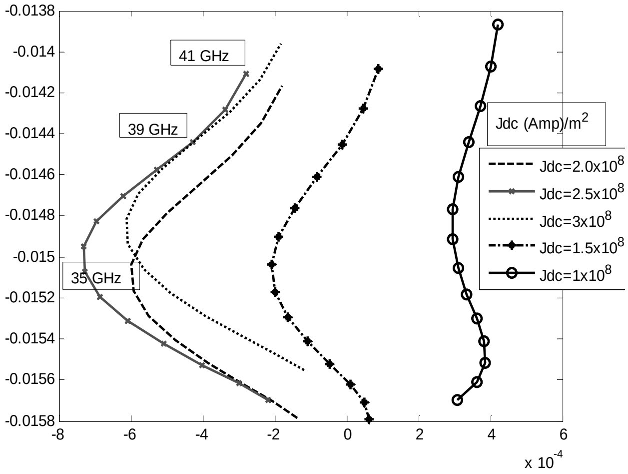

Fig. 2 G-B plot of Si-based IMPATT for different d.c bias current density.

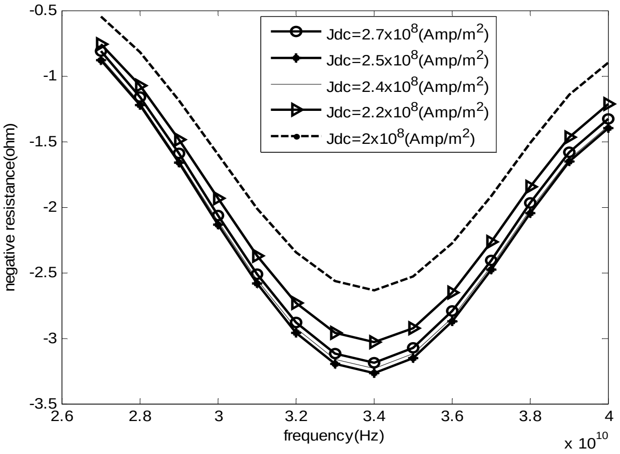

Fig. 3 Negative resistance plot of Si-based IMPATT for frequency variation in Ka band

It is observed from Fig. 3 that the negative resistance values are different for different dc current density and the peak negative resistance values are obtained at different frequency for different current density values. It is observed negative resistance is remarkable high, for the current density value 2.5×10^{8} Amp/m^{2}. Also the estimation of device stability through quality factor Q=B/G shown in Fig 4.

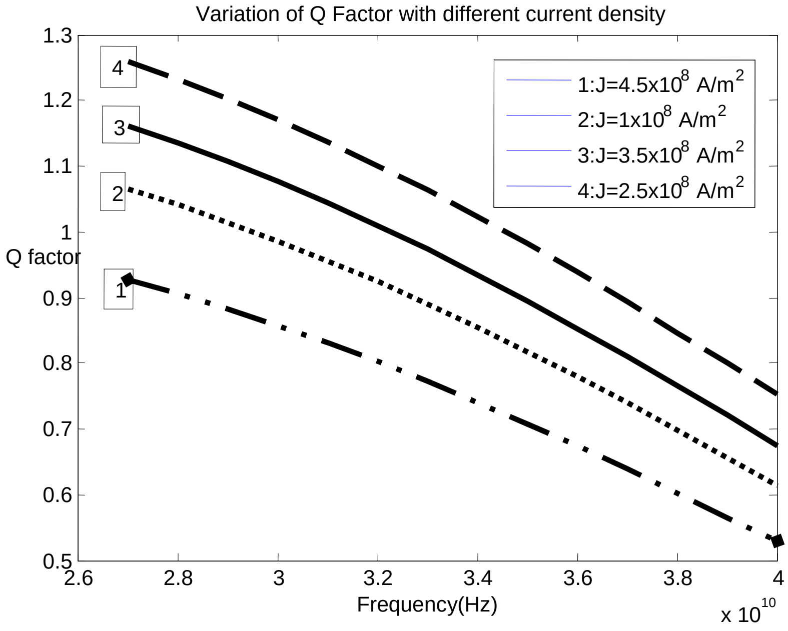

Fig. 4 Quality Factor Variation of Si based IMPATT with frequency for different current density at Ka- Band

The high ionization rate raises the electric field maximum near the junction to a high value and provides a high field gradient. These two facts would enhance the carrier multiplication process near the junction, which in turn would localize the avalanche region of the 3Cbased SiC IMPATTs providing a high value of drift voltage drop. A localized avalanche region width would increase the device efficiency and the high value of drift voltage drop would push up the power output of the device. But due to localized avalanche region, noise also increase at the output of the device which degrades the device performance. So a crucial noise performance analysis of Si and different compound semiconductor based IMPATT are studied in detail.

Hence a Noise-Power tradeoff is necessary before reaching to any conclusion. Such a noise power trade off can be given by Noise Measure which is by definition [Gummel (1967), Hermann (1971)]:

$$M = (\langle v^2\rangle/df)/4KT(-R) \tag{6}$$

$\langle v^2\rangle/df$ is the mean square noise voltage per band width (noise spectral density) which can be computed from the following equation [9] given below :

$$\langle v^2\rangle/df = (2q/Jo.A).(1+W/x_A)^2/\acute{\alpha}^2 \tag{7}$$

W and x_A are the depletion and avalanche region width respectively. Jo is the D.C current density, A is the area of the diode, K is Boltzmann constant T is temperature in Kelvin. (-R) is the real part of the device impedance. Noise Measure decreases with increasing value of negative resistance (-R). So this negative resistance (-R) has a crucial role on the noise performance of IMPATT diode. Negative resistance plots variation with frequency of Si and different compound semiconductor based IMPATT are shown in the following figure. It is observed that negative resistance value is maximum for 3C- SiC based IMPATT and is less noisy with comparison of others semiconductor based IMPATT. Noise Measure is also obtained for different semiconductor based IMPATT. 3C-SiC has minimum noise measure value 58.64 dB at 33 GHz frequency at Ka Band.

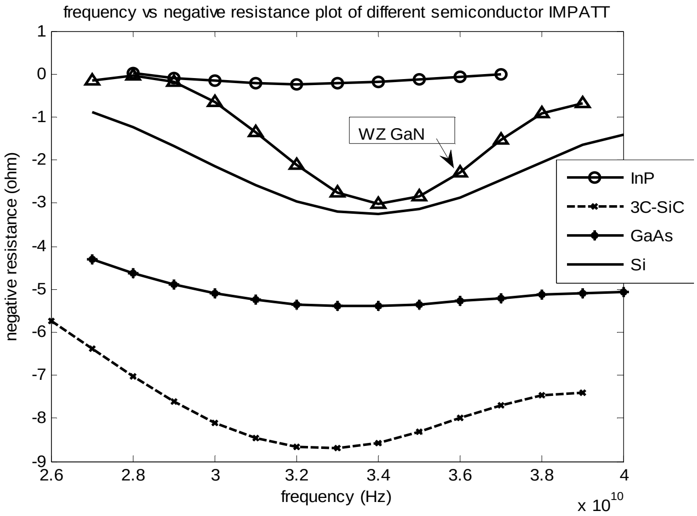

Fig. 5 Variation of Negative Resistance with frequency of different semiconductor based IMPATT

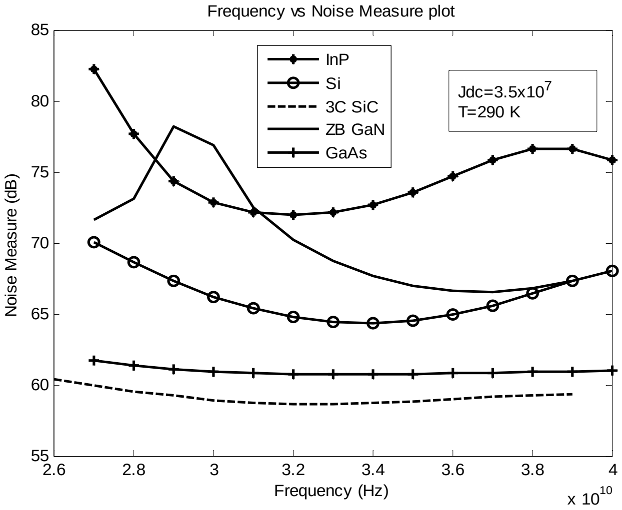

Fig. 6 Variation of Noise Measure (dB) with frequency of different semiconductor based IMPATT

Fig. 7 shows the “shot-noise ratio” defined as the mean-squared current of the equivalent parallel current generator, normalized to the shot noise [Panda (2009)] associated with the dc current:

$$R = \langle i^2 \rangle / 2.q.I_{dc}.df \quad (8)$$

$\langle i^2 \rangle/df$ is the mean square noise current per bandwidth.

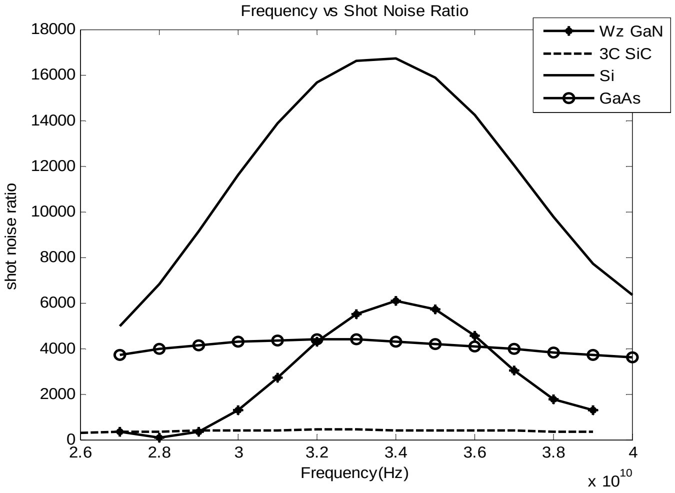

Fig. 7 Variation of shot noise ratio with frequency of different semiconductor based IMPATT

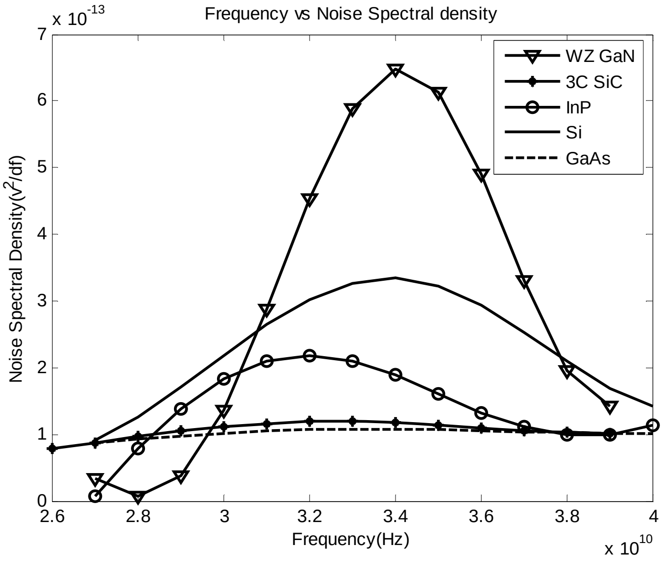

Fig. 7 Variation of noise spectral density ($V^{2/}$/df) of different semiconductor based IMPATT

TABLE 1.
Materials parameters.

Material Parameters	Si	GaAs	InP	3C SiC	Wz GaN
An (m^{-1})	$3.8x10^8$	$2.8x10^7$	$0.62x10^8$	$4.57x10^{10}$	$3.65x10^8$
Ap (m^{-1})	$2.25x10^9$	$2.8x10^7$	$2x10^8$	$5.13x10^8$	$6.44x10^8$
bn (V/m)	$1.75x10^8$	$6.85x10^7$	$1.08x10^8$	$5.24x10^9$	$0.99x10^8$
bp ((V/m))	$3.26x10^8$	$6.85x10^7$	$2x10^8$	$1.57x10^9$	$1.57x10^8$
Vns	10^5	$8x10^4$	$0.6x10^5$	$2.5x10^5$	$2x10^5$
Vps	$0.75x10^5$	$8x10^4$	$0.76x10^5$	$2.5x10^5$	$2x10^5$
ε_r	11.8	10.89	11.76	9.72	9.7

*An, bn are Ionization coefficient of electrons and Ap, bp are Ionization coefficient of holes.

* Vns and Vps are saturation velocity of electron and hole respectively and ε_r is the relative dielectric constant of the material.

α_n and α_p are rapidly increasing function of electric field. Experimentally obtained values of α_n and α_p can be approximately fitted with the empirical formula, α_n = An exp((-bn/E))* and α_p = Ap exp(-bp/E) respectively.

TABLE 2.
Simulated small signal parameters.

Diode base material	Diode Structure	Peak operating frequency (GHz)	Dc bias current density	Peak negative resistance (ohm)
Si	Flat DDR	34	$2.5x10^8$	-3.2635
GaAs	Flat DDR	33	$3.5x10^7$	-5.39
InP	Flat DDR	32	$3.5x10^7$	-0.26
3C SiC	Flat DDR	33	$3.5x10^7$	-8.70
Wz GaN	Flat DDR	34	$5x10^8$	-3.027

TABLE 3.
Simulated and noise parameters:

Diode base material	Peak Operating frequency (G Hz)	Minimum Noise Measure (dB)	Noise Spectral density (Volt^{2}sec)	Shot Noise Ratio
Si	34	64.38	$3.34x10^{-13}$	$1.671x10^4$
GaAs	33	60.71	$1.08x10^{-13}$	$4.37x10^3$
InP	32	71.98	$2.73x10^{-13}$	$7.66x10^8$
3C SiC	33	58.64	$1.19x10^{-13}$	$4.27x10^2$
Wz GaN	34	64.70	$6.484x10^{-13}$	$6.053x10^3$

Another two crucial factors, parasitic series resistance [Mitra (1993)] and temperature effect on device noise performance also observed. It is shown from fig 7 noise measure is increased with increasing value of parasitic series resistance. Series resistance has some detrimental effects on the noise performance.

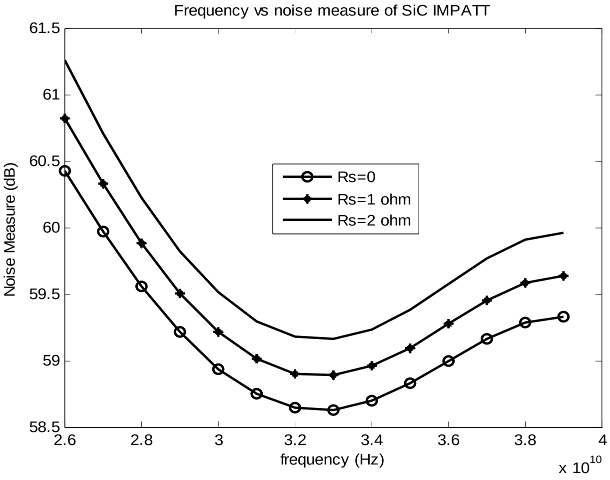

Fig. 7 Variation of Noise Measure (dB) with frequency with some assumed values of parasitic series resistance of 3C SiC based IMPATT

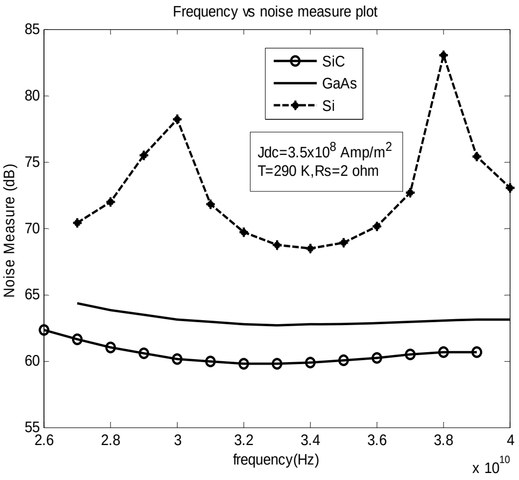

Fig. 8 Variation of Noise Measure (dB) with frequency of different semiconductor based IMPATT with assumed parasitic series resistance value

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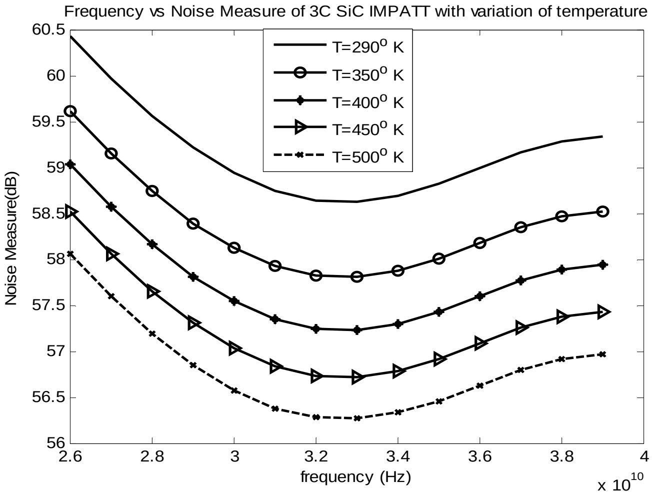

Fig. 9 Variation of noise measure (dB) with frequency for temperature variation

4. Conclusions:

A model is developed for a comparative study of noise performance of different semiconductor like Si, GaAs, InP, Wz GaN and 3C SiC based IMPATT diode. It is found from the results that the device noise behavior strongly depends on the negative resistance values. Noise Measure is inversely proportional with the value of negative resistance of the device. 3C SiC based IMPATT shows maximum negative resistance value of -8.7 ohm at 33 GHz in Ka-Band and thus having minimum noise measure. Short circuit mean square noise current, normalized with total dc current is defined as shot noise ratio which is minimum for 3C SiC and Wurtzite GaN diodes. If series parasitic resistance is considered then 3C SiC diode gives better performances comparing with others semiconductor based IMPATT. It is also found that the avalanche noise of diode decreases with increasing temperature. Thus, this simulation method developed by the authors may prove to be useful for the designing of low-noise IMPATT diodes. It is emerged that SiC based IMPATT is most powerful device comparing with other IMPATTs for its low noise performance.

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