Impact of Local-Negative-Feedback on the MRS Avalanche Photodetector Operation

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Abstract—Metal-Resistance-Semiconductor (MRS) photodetectors are characterized by a resistive layer placed in series to an avalanching region. In this paper, we report the characterization of such devices, we define a parameter extraction procedure, and we derive a quantitative model of the MRS operation. Due to the presence of the ohmic layer, the detector works as an ensemble of pixels with separately stabilized operating bias. In this way, compared to avalanche photodiodes (APD’s), MRS achieve superior gain uniformity with the same sensitive area. However, there are still aspects of the fabrication technology and of the detector structure which have to be improved.

Index Terms—Avalanche photodiodes, near-infrared detectors, photosensors.

I. INTRODUCTION

PHOTODETECTORS with large area and high sensitivity, down to single- or few-photon level, in the visible and near-infrared wavelength range [1], [2] as well as detectors for tracking ionizing particles [3], [4] are required in many applications. Avalanche photodiodes (APD’s) are the most used detectors for few-photon detection. However, people working with APD’s with such capability often complain about the small size of their sensitive area. Even if semiconductor technology is unceasingly improving, the reliable fabrication of APD’s with sensitive area larger that 1 mm$^2$ is still far from being an easy task. Refined technologies make it possible to achieve about 1% spreading of the breakdown voltage over a 500-μm diameter device. Many research and industrial labs are working to pursue better yield and narrower spread of APD characteristics.

A nonuniform APD may be seen as a parallel connection of many elementary devices, with individual breakdown voltages $V_{Bj}$ slightly different from the nominal breakdown voltage $V_B$ of the device. If the detector is biased by an external voltage source $V_R$, the $V_B$ spreading causes a dramatic change to the avalanche multiplication gain across the detector area. To a first-order approximation, the multiplication gain of a junction is given by the empirical formula

$$M_j(V_R) = \frac{1}{1 - \left(\frac{V_R}{V_{Bj}}\right)^n}$$

(1)

where $n$ is a fitting parameter depending on the junction doping profiles. The changes of $M_j$ from the nominal value $M$ due to a nonuniformity of $V_B$ can be derived by differentiating (1)

$$\frac{\Delta M_j}{M} = -n \cdot (M_j - 1) \cdot \frac{\Delta V_{Bj}}{V_B}.$$  

(2)

In a typical junction with $n = 2$, at $M = 100$ even a 1% spreading of $V_{Bj}$ causes more than a 100% variation of $M_j$.

The idea leading to Metal-Resistance-Semiconductor (MRS) photodetectors is to overcome the limitations due to nonuniformity, by fabricating a large area device acting as a parallel connection of smaller photodiodes, each of them biased through a ballast series resistor $R_j$, as shown in the inset of Fig. 1. In this way, the $V_B$ spreading causes a less dramatic variation of the multiplication gain. As an example, let us consider the elements with the lowest $V_{Bj}$. In a conventional APD, these elements would feature a much higher current density than the rest of the device. Instead, in the MRS structure a local current increase causes a voltage drop across the corresponding ballast resistor, which lowers the bias of the element. This negative feedback equalizes the current multiplication across the device area.

More quantitatively we may write that the reverse bias voltage $V_j$ across the junction of the $j$th element is given by

$$V_j = V_R - R_j \cdot M_j \cdot I_{0j}$$

(3)

where $I_{0j}$ is the primary current in the $j$th element due to thermal generation and photon absorption. By differentiating (1) and taking into account (3), it turns out that the multiplication gain spreading is now given by

$$\frac{\Delta M_j}{M} = -n \cdot (M_j - 1) \cdot \frac{\Delta V_{Bj}}{V_B} \cdot \frac{1 + R_j}{r_j}.$$  

(4)

Due to the presence of the ohmic layer, the detector works as an ensemble of pixels with separately stabilized operating bias. In this way, compared to avalanche photodiodes (APD’s), MRS achieve superior gain uniformity with the same sensitive area. However, there are still aspects of the fabrication technology and of the detector structure which have to be improved.

Fig. 1. Current–voltage characteristics of an APD biased through a high-value ballast resistor (inset). The APD operating point is more stabilized, compared to the case of constant bias (vertical load line).
where $r_j$ is the dynamic resistance of the junction

$$r_j = \frac{dV_j}{dI_j} = \frac{V_j}{I_{0j}} \cdot \frac{1}{n \cdot M_j \cdot (M_j - 1)}. \quad (5)$$

Note that the multiplication gain is effectively stabilized only if $R_j \gg r_j$. And this usually holds true for multiplication gains in excess of few hundreds.

The MRS photodetectors, recently proposed by Sadygov et al. [5] and V. Shubin and D. Shusakov [6], are characterized by a resistive layer placed on top of a multiplying junction. Even if these detectors are under evaluation in many laboratories, no quantitative models of their operation has been reported so far, experimental data is controversial, and advantages of such devices on standard APD’s are still not clear. Large part of our work was devoted to investigate MRS detectors in order to gain a better physical insight in their working principle and to provide a model consistent with the experimental results.

The paper is organized as follows. Section II deals with the structure of the samples. In Section III, we show how to extract the physical parameters of the MRS from photocurrent measurements. In Section IV, we discuss the dependence on the impinging power of the spatial distribution of the avalanche current, when a light spot is shined onto the detector area. The detailed model of the detector is discussed in Section V, with a quantitative discussion on the improved uniformity of MRS’s versus APD’s. Section VI is devoted to clarify an issue that has caused some confusion in literature: the comparison between the MRS noise performance and those of standard APD’s. Conclusions are dealt with in Section VII.

II. THE DEVICES

Our samples are MRS photodetectors developed and produced in Baku (Azerbaijan) and Kiev (Ukraine) by Z. Sadygov [5]. These devices have a sensitive area with a diameter of 0.9 mm. A schematic cross section is reported in Fig. 2. A shallow p-diffusion is formed on an n-doped silicon substrate and a 1000-Å thick Si$_x$O$_y$ resistive layer is grown on top. The back of the substrate is connected to an aluminum metallization, while the top electric contact is made with a 100-Å thick titanium layer, which covers the whole active area. The latter metallization is thin enough to be almost transparent to photons in the 200–600 nm wavelength range.

The devices are arranged as an 8-element linear array, with a pitch of 1.1 mm optimized for fiber readout. The reported quantum efficiency is 20% at 250 nm, with a maximum of 50% at 400 nm, with no antireflection coatings. More characteristics can be found in [7].

Fig. 3 shows the schematic energy band diagram and the electric field profile within the MRS, when the top titanium layer is negatively biased with respect to the n-substrate. The electric field peaks within the silicon substrate, but the p region is almost completely depleted and the electric field extends into the Si$_x$O$_y$ layer. Visible photons, with energy lower than the Si$_x$O$_y$ gap, cross both the titanium and resistive layers with negligible attenuation, and are eventually absorbed in the silicon depleted region. Photogenerated electrons drift toward the bulk, while holes move to the surface. If the electric field is high enough, carriers impact ionize, and start the avalanche process, like in normal APD’s.

The $x$ and $y$ percentages of the Si$_x$O$_y$ layer are chosen in order to have a resistive layer, and not an insulating layer as in MOS devices since it should provide the distributed network of ballast resistors. The avalanche current flowing through the Si$_x$O$_y$ layer is eventually collected by the top titanium contact. A current density, $J$, leads to a voltage drop across the resistive layer, given by

$$V_R = J \cdot \rho_R \cdot t_R \quad (6)$$

where $\rho_R$ and $t_R$ are resistivity and thickness of the Si$_x$O$_y$ layer, respectively. The corresponding electric field in the resistive layer is $E_R = J \cdot \rho_R$, as shown in Fig. 3. The doping level of the p shallow diffusion is chosen to avoid a low resistance path to the current, parallel to the Si$_x$O$_y$/Si interface, that may by-pass the resistive Si$_x$O$_y$ layer.

Since patents are pending on the detector fabrication process, no further information both on the structure of the samples and on the detailed doping levels were given to us by the technologists.
III. EXTRACTION OF DEVICE PARAMETERS

The characterization of the samples was performed with the devices placed on an X-Y micrometer translating stage, and a visible light beam from a calibrated lamp focused by an optical microscope. The lamp light was filtered with an interference filter centered at 450 nm. Current and voltage measurements were performed with a Keithley 617 electrometer, while a Newport power meter was constantly employed to monitor the optical power focused on the sample. All the instrumentation were computer controlled and data were averaged for filtering out the fluctuations at low light levels.

As soon as the devices are reverse biased, they show an unstable behavior: even at a constant reverse bias, the current undergoes significant fluctuations. This behavior may be due to the high concentration of trapping centers, localized at the Si–SiO$_2$ heterointerface and in the depleted region in the Si$_2$O$_5$ layer. The remedy for getting a reliable and constant read-out was to bias the samples at a constant 100-μA current for about 10 min at the beginning of the measurements. At any rate, the dark current of the samples has been continuously monitored since sometimes it featured slow drifts. Fig. 4 shows the typical MRS characteristics measured in the dark and by changing the size, of the illuminated spot, by means of pin-holes placed in the optical path of the focusing optics. During these latter measurements the optical power density was kept constant at 24 pW/μm$^2$.

The photocurrent due to the illuminated region can be obtained by subtracting the dark current from each of the four curves of Fig. 4. Fig. 5 shows the details of the resulting curves on a linear scale at high reverse voltages, above 48 V. The multiplication gain is so high (higher than $10^3$) that the current–voltage curves have a slope limited by the series resistance of the Si$_2$O$_5$ layer, $R_s$ given by

$$R_s = \frac{\rho_R \cdot \frac{t_R}{\pi}}{4 \cdot \phi^2}$$

where $\phi$ is the effective diameter of the avalanching region.

These current–voltage characteristics should be similar to those of an APD biased with a ballast resistance $R$. Therefore, they should be fitted by the equation

$$I = I_0 \cdot M = \frac{I_0}{1 - \left(\frac{V_R - R \cdot I}{V_B}\right)^n}$$

where $I$ is the avalanche current. Indeed, we have verified that (8) holds very well by taking $V_B = 47.53$ V, $n = 1.28$, and the resistances extracted from the slopes of the curves in the highest voltage range of Fig. 5.

Fig. 6 shows the dependence of $R$ as a function of the spot diameter $\phi_0$ together with the $(1/R)^{1/2}$ values, referred to the right hand-side vertical axis. The solid straight line in Fig. 6 represents the dependence

$$\sqrt{\frac{1}{R}} = \sqrt{\frac{\pi}{4 \cdot \rho_R \cdot t_R}} \cdot (\phi_0 + \Delta \phi)$$

which is simply obtained from (7), provided that a term $\Delta \phi = 31$ μm is added to the light spot size $\phi_0$. The presence of such additional term is not surprising, since carriers can diffuse out of the region defined by the light spot. Also the voltage drop across the resistive layer may build up an electric field component in the transverse direction which helps in spreading the carriers outside the light spot size. These effects make the signal current flow through an area with a diameter larger than $\phi_0$. Indeed, even to the limit $\phi_0 = 0$, the diameter of the avalanching region is not zero and the series resistance does not become infinite because the avalanche current flows through a filament with a finite diameter. The term $\Delta \phi$ gives the dimension of such a minimum filament.

As a final comment on the results shown in Fig. 6, we note that from the slope of the linear fitting of the right hand-side data, the Si$_2$O$_5$ resistivity of $\rho_R = 1.6 \cdot 10^6$ Ω·cm can be estimated. This value gives a specific series resistance of
Fig. 6. Series resistance (left axis) of the filament in which the avalanche current is flowing, as a function of the light spot diameter. From the slope of the linear fitting of the right hand-side axis data, a Si$_x$O$_{1-x}$ resistivity of $\rho_{R} = 1.6 \cdot 10^{6} \ \Omega \ cm$ is obtained.

160 MΩ for a 1-μm$^2$ sensitive area and a total resistance of 250 Ω in series to the 900-μm diameter MRS.

IV. SPATIAL CONFINEMENT OF THE AVALANCHE

The peculiarity of the resistive layer in MRS devices is that it must introduce a negative feedback in the polarization of each region of the active area. Therefore, the locality of the feedback is of primary importance since it allows to selectively compensate the breakdown disuniformity over the device. In order to study this confinement, the distribution of the current flowing both within and outside the illuminated spot must be investigated.

A detailed computation of the spatial distribution of the current density over the detector area is a complex task. The main mechanisms responsible for the spreading of the avalanche current around the illuminated spot are twofold: 1) the electrical crosstalk due to the Si$_x$O$_{1-x}$ layer actually does not allow a sharp transition among the illuminated region, with a high current density, and the surrounding kept in dark and 2) the multiplication process itself causes a lateral spreading of the avalanche, due to a diffusion assisted mechanism, discussed in detail in [8].

Let us imagine to ignore the former crosstalk effect, thus neglecting the electric field component in the direction parallel to the junction. In this way, by integrating the carrier continuity equations over the direction orthogonal to the junction plane, it can be found that the current density $J(r)$ satisfies the equation [8]

$$D \cdot \nabla^2 J = \frac{J}{\tau} + g(r) \quad (10)$$

where $r$ is the distance from the center of the illuminated spot, $D$ is the average carrier diffusion coefficient, $\tau$ is the multiplication time constant of the ionization process, and $g(r)$ takes into account the carrier generation rate due to signal photons or thermal processes. Besides the oversimplifying assumption made, the problem is still of difficult solution, since the multiplication time constant is strongly dependent on the electric field in the semiconductor. Therefore, the voltage drop caused by the current across the ohmic layer makes $\tau$ depending on $J(r)$. The problem is nonlinear and its solution gets more cumbersome also taking into account the other nonlinear dependence of (8).

We decided to assess the role of the contribution $\Delta \phi$ on the spot diameter $\phi_0$ with a new set of experiments. Since the voltage drop across the ohmic layer depends on $J(r)$ that, in turn, depends on the impinging optical power, $P$, we measured the photocurrent as a function of the optical power by using a fixed 45-μm diameter light spot (Fig. 7). Due to the avalanche multiplication gain, the dependence is nonlinear and, therefore, the size ($\phi_0 + \Delta \phi$) is expected to be not linearly dependent on $P$. From these data we extracted the values of the resistance, $R$, as explained before. Again, we used (9) and we obtained the dependence of the effective diameter on power by plotting the $(1/R)^{1/2}$ values versus the natural logarithm of the optical power (Fig. 8). From the fitting we derive the dependence

$$\phi_0 + \Delta \phi = \sqrt{1/R} \cdot \sqrt{A} \cdot \rho_{R} \cdot \tau / \pi = \phi_0 + 2 \cdot L \cdot \ln \frac{P}{P_0} \quad (11)$$

where $2 \cdot L = 27.4 \ \mu m$ is the slope of the fitting line and $P_0 = 9.5 \ nW$ is the power level corresponding to the spot diameter $\phi_0 = 45 \ \mu m$. The power $P_0$ may be read as minimum optical power beyond which the avalanche process begins to sensibly spread out of the illuminated spot.

The logarithmic dependence of (11) has a simple interpretation: Let us assume that the current density, almost constant to a value $J_S$ within the illuminated spot, exponentially decays outside it according to

$$J(r) = J_S \cdot e^{-r/L} \quad (12)$$
In this framework, the effective avalanching area may be defined as the region where the current density $J(r)$ is higher than a threshold value $J_0$. From (12), we get that the avalanching area is larger than the spot size diameter $\phi$ by

$$\phi_0 = 2 \cdot L \cdot \ln \left( \frac{J_m}{J_0} \right) = 2 \cdot L \cdot \ln \left( \frac{P}{P_0} \right).$$

(13)

The parameter $L$ is the characteristic length of the exponential decay and, in the operating conditions, it is $L = 13.7 \, \mu m$. Beyond about three times the length $L$ from the edge of the light spot, i.e., at about $40 \, \mu m$, the signal photocurrent may be considered negligible and any perturbation of the junction bias due to the presence of the impinging light vanishes.

Therefore, the MRS devices under test can be modeled as many elementary $80-\mu m$ diameter APD’s, as shown in Fig. 9. The resistive layer resistance of each pixel, $R_R = 32 \, k\Omega$ [see (7)], acts as a localized ballast resistor [see (8)]. The avalanche current in each pixel affects the bias only within the pixel itself. Pixels illuminated by spots of different intensities have correspondingly different $R_R$ values (see Fig. 8) and voltage drops across the layer, as highlighted by the dashed line in Fig. 9. If two light spots, e.g., generated by two bunches of photons, impinge on the detector area at a distance greater than about $80 \, \mu m$, they generate two distinct and independent avalanche processes.

V. UNIFORMITY OF MRS SENSITIVITY

From the quantitative model derived in the previous section, it is now possible to assess the improvement of MRS on a standard APD with the same active area. Each elementary APD into which the MRS is subdivided has a localized negative feedback which stabilizes the operating point and, therefore, the sensitivity of the detector as a whole. Fig. 10 shows the operating point of one pixel, when a reverse bias of $V_{\text{MRS}} = 47.95 \, V$ is applied to the MRS and a current of $I = 14.2 \, \mu A$ is measured after the application of a primary photocurrent $I_{\text{ph}} = 14.5 \, nA$. The average multiplication gain is $M = 1000$ in agreement with (8).

The MRS load line is slanted, due to the $32 \, k\Omega$ series resistance, while the load line of a normal APD, with no ballast resistor, would be vertical since it would be biased at a constant $V_{\text{APD}} = 47.5 \, V$. Fig. 10 highlights the shift of the measured avalanche current in the two devices when a 0.1% spreading of the breakdown voltage is considered. In the above conditions, the MRS’s gain changes of about 10%, while the standard APD would suffer more than 100% fluctuations. These values are obtained from (2) and (4), by taking into account the differential resistance $r_d = 2000 \, \Omega$ [from (5)].

In particular, the improvement in the stabilization of the operating point gets better, the higher the series resistance $R_R$ and the lower the differential resistance $r_d$, i.e., the higher the multiplication gain, as can be seen from (5). It is important to note that, even if the standard APD would be biased through an external ballast resistor, its uniformity will not improve because $R_R$ will act on the whole active area, without any selectivity on localized disuniformities.

In order to be fair, it must be stressed that nowadays MRS devices are fabricated with a poorer technology compared to standard APD’s. The interface between silicon and the resistive Si$_x$O$_y$ layer suffers from a high density of defects.
Fig. 11. Effective excess noise factors in MRS devices with different resistive layers. Both pure hole (solid lines) and electron (dashed lines) ignitions are considered.

and trapping centers, as already mentioned in Section III. The reproducibility of the SiOx layer is still not assessed. Moreover, the samples under test showed an aging after some months, that lead to an increased dark current level, and a peculiar slow shift of the measured current on a tens of seconds time scale. Both effects are still under evaluation in our labs. Therefore, besides the reported advantages of the MRS working principle over the standard APD one, more work must be done from the fabrication side, in order to improve the processing and the reliability.

VI. EXCESS NOISE FACTOR

In literature MRS devices are claimed to give a reduced excess noise factor. In this section, we will show that even if this statement can be true, in practice it does not mean a better signal-to-noise ratio (SNR), as sometimes erroneously assumed. Let us write the expression of the shot noise spectral density [9]

$$\frac{\Delta I^2}{\Delta f} = 2 \cdot q \cdot I_{ph} \cdot M^2 \cdot F(M)$$ (14)

where, again, \(I_{ph}\) is the primary current generated, for instance, by a continuous wave photon flux, \(M\) is the multiplication gain, \(q\) is the electron charge, and \(F\) is the excess noise factor. For an APD, where the multiplication process is triggered by holes, the excess noise factor is given by [9]

$$F(M) = M \cdot \left[1 - (1 - k) \cdot \left( \frac{M - 1}{M} \right)^2 \right]$$

$$= k \cdot M + (1 - k) \cdot \left( 2 \cdot \frac{1}{M} \right)$$ (15)

where \(k = \alpha/\beta\) is the ratio between the electron, \(\alpha\), and hole, \(\beta\), ionization coefficients. In silicon under high electric fields (\(k \approx 10\)) this factor starts from 1 for \(M = 1\) and quickly rises to 10 for \(M = 100\), and to 1000 for \(M = 200\). If the primary carriers to trigger the avalanche process were electrons, (15) would be written with \(k = \beta/\alpha\). Fig. 11 shows the dependence of a standard APD’s excess noise factor on the multiplication gain, for the two case of pure hole (\(k = 10\), solid lines) and electron (\(k = 0.1\), dashed lines) primary ignitions.

With the MRS samples under test, there is no pure ignition of holes or electrons, so the excess noise factor cannot properly be defined by (15). What really happens is a mixed contribution of both holes and electrons, depending on the wavelength of the radiation and on the depth of the primary absorption [9]. However, since the electric field is peaked at the top of the silicon depleted region (see Fig. 3), it can be reasonably assumed that the avalanche process is mainly triggered by holes (i.e., \(k = 10\), solid lines).

The reduction of the excess noise factor in MRS devices can be easily justified by studying the simple electronic front-ends shown in Fig. 12, where both an MRS and a standard APD have been connected to a transimpedance amplifier or a charge integrator. In the APD case, both the noise expressed by (13) and the signal current \(I = I_{ph} \cdot M\) are collected by the virtual ground. Instead, in the MRS case, both currents suffer from the shunt partition between the differential small-signal resistance \(r_d\) and the resistance \(R_R\) of the SiOx layer. The overall excess noise factor of the MRS is, therefore

$$F_{MRS}(M) = \frac{\Delta I^2}{\Delta f} = \frac{V_B}{r_d + R_R} \cdot \frac{1}{M^3} \cdot \frac{k}{\alpha}$$ (16)

At high gains, it decreases as \(M^{-3}\), instead of rising proportional to \(M\) as in a standard APD [see (15)]. The reason is the dependence of \(r_d\) on \(M^{-2}\) as given by (5). This trend is confirmed by Fig. 11, which shows the complete dependence of \(F_{MRS}\) on the multiplication gain for both hole and electron primary injections.

However, it is not correct to talk about the advantages of the reduced noise, if one does not take into account the corresponding reduction of the output signal. In fact, for continuous wave or quasi-stationary light applications, the signal is partitioned in the same way of the noise. At very high gains, the multiplied primary photocurrent is short-circuited by the differential resistance, and the output signal reduces to

$$I_S = I \cdot \frac{r_d}{r_d + R_R} \approx \frac{V_B}{R_R} \cdot \frac{1}{n} \cdot \frac{1}{M}$$ (17)

At high gains the MRS output signal current decreases as \(M^{-1}\), instead of linearly rising with \(M\), as in a standard.
APD. For quasi-stationary illumination and in the case of signal-limited shot noise, the SNR of each pixel of the MRS is

$$\text{SNR}_{\text{MRS}} = \frac{I_{\text{ph}} \cdot M \cdot \left( \frac{\gamma_d}{\gamma_d + R_R} \right)}{\sqrt{2 \cdot q \cdot I_{\text{ph}} \cdot M^2 \cdot F \cdot \left( \frac{\gamma_d}{\gamma_d + R_R} \right)^2} \cdot \Delta f}$$

$$= \frac{I_{\text{ph}} \cdot M}{\sqrt{2 \cdot q \cdot I_{\text{ph}} \cdot M^2 \cdot F} \cdot \Delta f} = \text{SNR}_{\text{APD}}$$ (18)

where $\Delta f$ is an arbitrary bandwidth of interest. As can be seen, it is actually equivalent to that of a standard APD. Therefore, there is no advantage in employing MRS detectors for quasi-stationary light applications. All the more reason because a flicker noise ($1/f$) contribution must be added to MRS devices, due to the fact that their structure is more prone to defects and have higher trap density, compared to normal APD’s.

VII. CONCLUSIONS

We have derived a complete quantitative model of MRS detectors, based on an extensive set of experimental results. The devices tested can be modeled as a matrix of elementary APD’s, with a ballast resistance ($R_R = 32$ kΩ) in series to each pixel.

Regions illuminated by spots of different intensities have correspondingly different resistances (see Fig. 6) and voltage drops across the layer. If two light spots, e.g., generated by two bunches of photons, are far apart more than 80 µm they do not interfere with each other. These characteristics make MRS’s promising for the parallel detection of multi-photon signals and ionizing particles. By a proper tailoring of the resistive layer material, MRS performance can be adjusted and MRS parameters can be calculated, according to the parameters extraction procedures presented in the paper.

It must be stressed that current MRS devices are fabricated with a poorer technology compared to standard APD’s. The interface between silicon and the resistive Si$_x$O$_y$ layer suffers from a high density of defects and trapping centers, as already mentioned in Section III. The reproducibility of the Si$_x$O$_y$ layer is still not assessed. Moreover, the samples under test showed an aging after some months, that lead to an increased dark current level, and a peculiar slow shift of the measured current on the time scale of tens of seconds. Both effects are still under evaluation in our laboratories.

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