# Ideal RESURF Geometries

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***Abstract*— In order to maximize the OFF-state breakdown voltage (BV) of semiconductor devices, the slope of the electric field in the drift extension along the current flow direction ($E_x$ field) should be zero. This is achieved using the reduced surface field (RESURF) effect. This paper demonstrates a method to construct devices that obey Poisson's equation and satisfy the ideal RESURF condition giving zero slope in $E_x$ throughout the 2-D device region. The designs are obtained by shaping the device geometry and the boundaries and by applying the proper potentials at the boundaries. Using this method, ideal designs of the drift extension have been derived for devices based on graded doping, graded thickness, and graded field-plate potential. In addition, 2-D solutions have been derived for periodic superjunction device geometries. A solution for devices that combine several types of field shaping is demonstrated. Finally, the effect of nonideal geometries on the BV in more realistic geometries is discussed.**

***Index Terms*— Charge balance, electric field, field plate, high voltage, power MOSFET, reduced surface field (RESURF), Silicon-on-insulator, superjunction.**

## I. INTRODUCTION

BREAKDOWN of semiconductor devices occurs due to an avalanche of charge carriers initiated by high electric fields in reverse biased junctions [1], [2]. In order to increase the breakdown voltage (BV) of high-voltage semiconductor devices, a relatively long drift extension is, therefore, used to reduce the electric fields [2]. It is commonly known [3] that the OFF-state BV is maximized by ensuring that the electric field in the drift extension along the current flow direction ($x$-direction) satisfies

$$\frac{\partial E_x(x, y)}{\partial x} = 0. \tag{1}$$

This is defined as the ideal RESURF condition for the $E_x$ field. For most device designs, the solution of Poisson's equation does not obey (1) throughout the 2-D geometry. As will be shown, an ideal RESURF geometry requires the boundaries to be shaped in a special manner, an aspect that has not been dealt with in [4]–[10]. If the ideal field condition is not satisfied everywhere in the $xy$ plane, the BV of these devices is lower than for those satisfying (1) at a given drift extension length $L$. For this reason, the investigation of device designs that provide the solutions of Poisson's equation obeying (1) is worthwhile. Exact solutions of (1) are also useful for the performance optimization of other semiconductor devices, such as FinFETs, nanowire or gate-all-around FETs and deep submicrometer transistors [11].

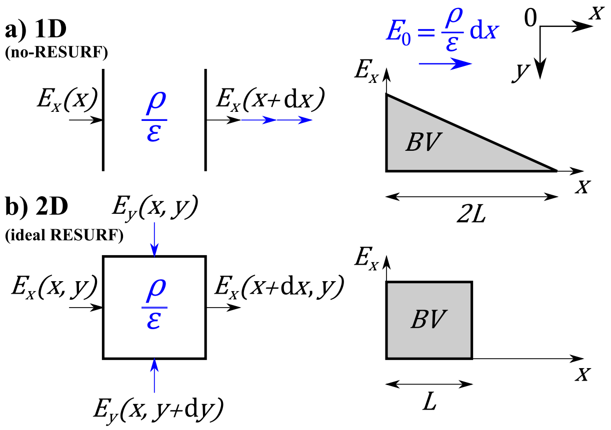

Fig. 1. Schematics explaining the RESURF principle by considering an infinitesimal part of the drift region containing a constant charge density $\rho$ and having dielectric constant $\varepsilon$. (a) 1-D device in the absence of the RESURF effect. Since $(\partial E_y/\partial y) = 0$, according to Poisson's equation (2), the electric field $E_x$ has a slope $(\partial E_x/\partial x) = (\rho/\varepsilon)$. (b) Ideal field condition can be satisfied by applying an electric field in the $y$-direction with gradient $(\partial E_y/\partial y) = (\rho/\varepsilon)$, such that $(\partial E_x/\partial x) = 0$, and $E_x$ is constant.

The Reduced Surface Field (RESURF) [12], [13] principle is based on reducing the field in the current flow direction ($x$-direction) by introducing a perpendicular field gradient (in the $y$-direction), as shown in Fig. 1. In the absence of RESURF [Fig. 1(a)], with zero $E_y$-field gradient, the $E_x$ field has a gradient $(\partial E_x/\partial x) = (\rho/\varepsilon)$, where $\rho$ is the charge density and $\varepsilon$ is the dielectric constant. In Fig. 1(b), the RESURF effect is implemented using a $(\partial E_y/\partial y)$-field gradient in the drift region. Since according to Poisson's equation, $(\partial E_x/\partial x) + (\partial E_y/\partial y) = (\rho/\varepsilon)$, it follows that for $(\partial E_y/\partial y) = (\rho/\varepsilon)$, the gradient $(\partial E_x/\partial x)$ becomes zero, and the ideal RESURF condition (1) is satisfied. The graphs in Fig. 1 (right) illustrate that at identical maximum field and BV, a 2-D drift extension needs

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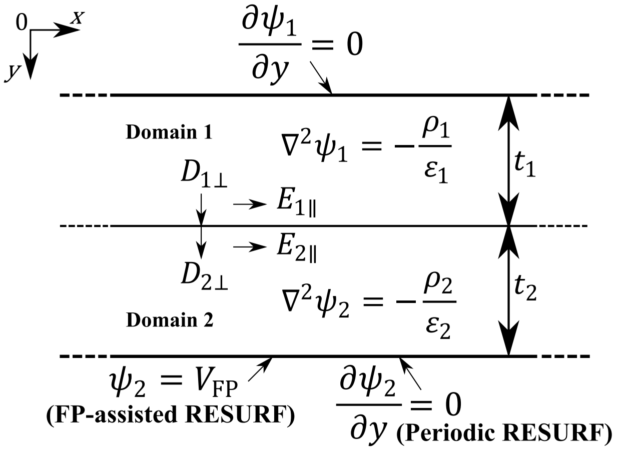

Fig. 2. Schematic potential distribution $\psi(x, y)$ in the drift extension of ideal RESURF devices. Only half of the symmetric structure is shown. The device is mirror symmetric in the boundary at $y = 0$, and a field plate (at potential $V_{\mathrm{FP}}$) or periodic boundary condition is placed at $y = t_1 + t_2$.

only half of the length compared with a 1-D one. The BV is equal to the gray area under the graphs.

An additional advantage of the application of RESURF is that a higher doping in the drift region can be used. While increasing the doping would lead to a reduction of the BV in a 1-D device [Fig. 1(a)], the RESURF effect can be used to balance the increase in charge density by a higher vertical field gradient $(\partial E_y/\partial y)$. This further improves the specific ON-resistance $R_{\mathrm{ON}}A$-$BV$ tradeoff of power devices [14].

This paper focuses on constructing device designs that satisfy the ideal RESURF [Fig. 1(b)] throughout their 2-D geometry. For the sake of generality, the $x$-direction and the $y$-direction in this paper, respectively, refer to the direction of the current flow and any of the two directions perpendicular to it, independently of the device orientation with respect to the wafer plane. Therefore, the proposed designs can be implemented in both lateral and vertical devices with RESURF fields acting either in or out of the wafer plane.

The rest of this paper is organized as follows. Section II describes ideal RESURF geometries in 2-D that are derived by an exact analytical solution of Poisson's equation. Two types of geometries are discussed: 1) geometries that use field plates to generate the field gradient $(\partial E_y/\partial y)$ and 2) periodic geometries that use superjunctions to satisfy the ideal field condition. Section III shows implementation examples of the different types of ideal RESURF solutions. Section IV shows an example of a combined RESURF device. Section V discusses the effect of deviations from the ideal case on the BV. Finally, the conclusions are presented in Section VI.

## II. DERIVATION OF THE IDEAL RESURF SOLUTION

In this section, analytical solutions of Poisson's equation are derived that satisfy the ideal RESURF condition $(\partial E_x/\partial x) = 0$. The assumed geometry and boundary conditions are shown in Fig. 2. The structure consists of two domains, with charge densities $\rho_{1,2}$ and dielectric constants $\varepsilon_{1,2}$. The interface between the domains is assumed to be ideal, i.e., free of interface charges. At this interface, the perpendicular displacement field $D_\perp$, the parallel field $E_\parallel$, and the potential $\psi$ need to be continuous. Domain 1 is made of a semiconductor material that has the purpose to block current at high voltages in the OFF-state and to conduct current in the ON-state. The main purpose of domain 2 is to generate the field gradient $(\partial E_y/\partial y)$ needed for the RESURF effect in the current blocking state. Domain 2 is either made of a dielectric without fixed charge $(\rho_2 = 0)$ or of a semiconductor material with opposite charge density compared with that in domain 1 $(\rho_2 \neq 0)$. Since the structure is intended for blocking voltages up to the BV, the right boundary is at a potential $\psi = \mathrm{BV}$, whereas the left boundary is at the ground $(\psi = 0)$. The geometry, and potential $\psi(x, y)$, is symmetrical with respect to the reflection in the $x$-axis $[(\partial \psi(x, y)/\partial y)|_{y=0} = 0]$. The nonperiodic geometries are terminated by a field plate at the boundary $y = t_1 + t_2$, which is held at a field-plate potential $\psi(x) = V_{\mathrm{FP}}(x)$. The periodic geometries are also symmetric with respect to reflection in the line $y = t_1 + t_2$, and therefore require $(\partial \psi/\partial y) = 0$ at this interface. The dielectric constants in both domains $\varepsilon_{1,2}$ are assumed to be position independent, since the spatial inhomogeneities due to process variations in a slab of semiconductor or dielectric material have negligible effects on the field distribution. A continuous significant grading of $\varepsilon_2$ for achieving optimal RESURF, suggested in [15], requires custom technology not readily available today, and therefore has not been considered in this paper.

For constant $\varepsilon$, Poisson's equation needs to be obeyed

$$\nabla^2 \psi(x, y) = \frac{\partial^2 \psi(x, y)}{\partial x^2} + \frac{\partial^2 \psi(x, y)}{\partial y^2} = -\frac{\rho(x, y)}{\varepsilon}. \quad (2)$$

Potential distributions of the form $\psi(x, y) = -(\alpha x + \beta) f(y)/\varepsilon$ are considered, which satisfy both (1) and (2) if $(\alpha x + \beta)(\partial^2 f(y)/\partial y^2) = \rho(x, y)$. Since charge distributions with a zero or constant charge gradient are the most relevant for RESURF devices [4], [15]–[19], this paper focuses on the solutions of the potential distribution $\psi(x, y)$ with $(\partial^2 f(y)/\partial y^2) = 1$, such that $\rho(x, y)$ is a linear function of $x$ and is not a function of $y$

$$\rho(x, y) = \rho(x) = \alpha x + \beta \quad (3)$$

with $\alpha$ and $\beta$ being constants.

The function $\psi(x, y)$ satisfying (1) and (2), the conditions $\psi_1(0, 0) = 0$ and $\psi_1(L, 0) = \mathrm{BV}$, and (3) for any $(x,\ y)$ is found to be

$$\psi(x, y) = \frac{\mathrm{BV}}{L} x - \frac{\rho(x) y^2}{2\varepsilon} + c_1 y + c_2 \quad (4)$$

where $c_1$ and $c_2$ are the integration constants. In other words, (4) describes an exact ideal RESURF solution of Poisson's equation for charge distributions $\rho(x)$ that are either constant or have a linearly graded doping concentration in the $x$-direction. This solution needs to be extended to both the domains and suitable boundary conditions need to be found.

Using the symmetric boundary condition from Fig. 2, $(\partial \psi_1/\partial y) = 0$ at $y = 0$, the solution $\psi_1(x, y)$ inside domain 1 is found to be

$$\psi_1(x, y) = \frac{\mathrm{BV}}{L} x - \frac{\rho_1(x)}{2\varepsilon_1} y^2. \quad (5)$$

This solution can be extended to domain 2 using the continuity conditions at the interface between domain 1 and domain 2. These conditions ensure the continuity of the displacement field $D_\perp$ perpendicular to the boundary and the electric field $E_\parallel$ parallel to the boundary (see Fig. 2). When the interface is parallel to the $x$-axis (i.e., $t_1$ does not vary with $x$), the potential $\psi_2$ in domain 2 is given by

$$\psi_2(x, y) = \frac{\mathrm{BV}}{L}x - \frac{\rho_1(x)}{2\varepsilon_1}t_1\left[t_1 + 2\frac{\varepsilon_1}{\varepsilon_2}(y - t_1)\right] - \frac{\rho_2(x)}{2\varepsilon_2}(y - t_1)^2. \quad (6)$$

It thus has been shown that (5) and (6) satisfy both Poisson's equation and the ideal field condition throughout both domains. Moreover, they satisfy the boundary conditions along the line $y = 0$ and the continuity equations at the interface $y = t_1$.

For (5) and (6), to represent actual solutions of Poisson's equation, two challenges remain. First, the outer boundary conditions at $y = t_1 + t_2$ need to be satisfied. This will be discussed in Section II-A for nonperiodic and field-plate-assisted structures and in Section II-B for periodic structures. Next, the conditions $\psi = 0$ and $\psi = \mathrm{BV}$, respectively, on the left and right boundaries need to be satisfied for all $y$. This can be achieved by geometry shaping of these boundaries, as described in Section II-C.

### A. Field-Plate-Assisted RESURF

In nonperiodic structures, the RESURF gradient in the $y$-direction is created using a field plate. The field plate symmetrically terminates the structure at the top and the bottom of the drift extension. In order to satisfy the boundary condition, the potential on the field-plate $V_{\mathrm{FP}}$ needs to match that of the solution in (6), such that $\psi(x, y)|_{y=\pm(t_1+t_2)} = V_{\mathrm{FP}}(x)$. Thus, for a field plate located at $y = \pm(t_1 + t_2)$, the field-plate potential $V_{\mathrm{FP}}(x)$ is obtained by substituting $y = \pm(t_1 + t_2)$ in (6) resulting in

$$V_{\mathrm{FP}}(x) = \frac{\mathrm{BV}}{L}x - \frac{\rho_1(x)}{2\varepsilon_1}t_{\mathrm{eq}}(x)^2 - \frac{\rho_2(x)}{2\varepsilon_2}t_2(x)^2 \quad (7)$$

where the equivalent thickness $t_{\mathrm{eq}}$ [15], [18] can be expressed in terms of $t_1$ and $t_2$ using

$$t_{\mathrm{eq}}(x) = \sqrt{t_1\left[t_1 + \frac{2\varepsilon_1}{\varepsilon_2}t_2(x)\right]}. \quad (8)$$

### B. Periodic RESURF

As an alternative to field plates, semiconductor domains with opposite charge density can be used to generate the gradient $(\partial E_y/\partial y)$. These periodic structures can be created by alternating domains 1 and 2 in an infinite stack of domains with constant thicknesses $2t_1$ and $2t_2$. Due to the repetitive, periodic nature of the superjunction stack, it is sufficient to show that the solution satisfies the boundary and continuity conditions at $y = 0$, $y = t_1$, and $y = t_1 + t_2$.

If the structure is periodic in the $y$-direction, the boundary conditions at $y = \pm(t_1 + t_2)$ do not only require the continuity of the potential $\psi(x, y)|_{y=\pm(t_1+t_2)}$ but also of its $y$-derivative. From symmetry considerations, this is only possible if $(\partial\psi/\partial y)|_{y=\pm(t_1+t_2)} = 0$. Applying this condition to (6) yields the well-known charge balance condition [6]

$$\rho_1(x)t_1 + \rho_2(x)t_2 = 0. \quad (9)$$

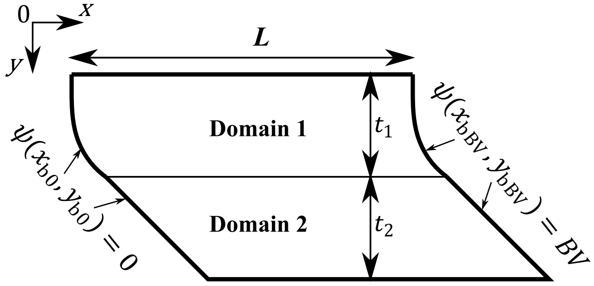

Fig. 3. Schematic of an example ideal RESURF structure that can be derived from Fig. 2 using the geometry shaping procedure in Section II-C. The left and right boundaries need to follow the shape of the equipotential lines in order to keep the potential distribution ideal.

This shows that in order to satisfy the ideal field condition, the charge distributions in the periodic domains need to satisfy (9), which requires the sign of the doping charge to alternate between the n-type and the p-type. If domain 2 is an ideal dielectric with zero fixed charge, such as in periodic dielectric RESURF (DIELER [20]), charge balance cannot be achieved, and (1) cannot be satisfied.

Equations (5) and (6) provide the RESURF solution in the field-plate-assisted case together with (7), and describe the ideal potential distribution in the periodic domains for superjunction devices together with (9). After having satisfied the interface boundary conditions, the geometry shaping procedure in Section II-C will be applied in order to satisfy the boundary conditions at the left and right terminals for both the periodic and nonperiodic devices.

### C. Geometry Shaping of the Left and Right Boundaries

The left and right boundaries of the structure can be described by a parametric equation $(x, y) = (x_b(s), y_b(s))$. The potential $\psi_b$ as a function of the position parameter $s$ at the boundaries is given by (5) and (6)

$$\psi_b(s) = \psi(x_b(s), y_b(s)). \quad (10)$$

The potential $\psi_b$ along the left $(x_{b0}, y_{b0})$ and right $(x_{b\mathrm{BV}}, y_{b\mathrm{BV}})$ boundaries of domain 1 is imposed to be a constant. In order to obtain boundary designs that satisfy this condition, a geometry shaping procedure is applied, which ensures that the boundaries run along an equipotential line of (5), as shown schematically in Fig. 3. Thus, the shape of the left and right boundaries is found according to (10) by finding the equipotential lines $(x_b, y_b)$ that satisfy the following equations:

$$\begin{cases} \psi(x_{b0}(s), y_{b0}(s)) = 0 & \text{(a)} \\ \psi(x_{b\mathrm{BV}}(s), y_{b\mathrm{BV}}(s)) = \mathrm{BV} & \text{(b).} \end{cases} \quad (11)$$

Some degrees of freedom are present in the choice of the shape on the left and right boundaries of domain 2. Suitable shapes can be chosen depending on the type of RESURF. If the structure cannot be terminated on equipotential boundaries, as in (11), a nonzero potential gradient on the boundaries will be present. In any case, ideal solutions are obtained as long as the boundary is shaped, such that the potential along the boundary obeys (10). It should be emphasized that the shaping procedure described in this section is important for inducing 2-D ideal RESURF solutions. Devices with straight boundaries at constant potential will usually not exactly obey (1) for nonzero doping $\rho_1$ (see Section V-A). After having derived ideal RESURF solutions, Section III will focus on providing examples of their implementation in several important cases.

## III. PROCEDURE AND EXAMPLES OF IDEAL RESURF STRUCTURES

In this section, several examples of ideal RESURF device architectures are given (see also [15]). In order to design a structure that yields an exact solution of Poisson's equation and satisfies the ideal RESURF condition (1), the following procedure is taken.

1) Choose BV and device length $L$, making sure that $(\mathrm{BV}/L)$ is smaller than the critical field $E_{\mathrm{crit}}$ (see Section V-A) to prevent the breakdown.
2) Choose the semiconductor thickness $t_1$.
3) For field-plate RESURF:
    a) choose one graded parameter $\rho_1$, $t_2$, or $V_{\mathrm{FP}}$;
    b) fix the other two (nongraded and constant) parameters making sure that junction, vertical and dielectric breakdown are prevented (see Section V-C);
    c) determine the gradient ($x$-dependence) of the graded parameter using (7).
4) For Periodic (superjunction) RESURF:
    a) fix $\rho_1(x)$.
    b) choose $t_2$ and $\rho_2(x)$ to satisfy (9).
5) Shape the left and right boundaries according to (11) making use of (5) and (6).

This procedure is demonstrated for several cases in this section. The procedure captures most practical cases, but does not yield all possible types of solutions, since one might also consider to grade two parameters, or to grade $t_1$ [21] or the dielectric constants $\varepsilon$ [7]. It is noted that the analytical solutions of the potential (5) and (6) are found to be in exact agreement with numerical solutions of Poisson's equations using COMSOL [22] within numerical accuracy. A further validation of the model has been proposed in [15] using TCAD simulations [23] for solving the semiconductor equations.

### A. Field-Plate-Assisted RESURF

By choosing one graded parameter in (7) [Step 3a)], the ideal RESURF solutions are demonstrated in some significant cases: 1) graded doping in domain 1 $\rho_1$ (Fig. 4); 2) graded field-plate potential $V_{\mathrm{FP}}$ (Fig. 5); and 3) graded thickness $t_2$ of domain 2 (Fig. 6). In each of the three figures, the solutions are shown for dielectric RESURF [$\rho_2 = 0$, subfigure (a)] and for p-n junction RESURF [$\rho_2 \neq 0$, subfigure (b)]. As can be seen, the equipotential lines are equidistant in the $x$-direction, showing that the ideal RESURF condition (1) is obeyed throughout the 2-D region in all the cases.

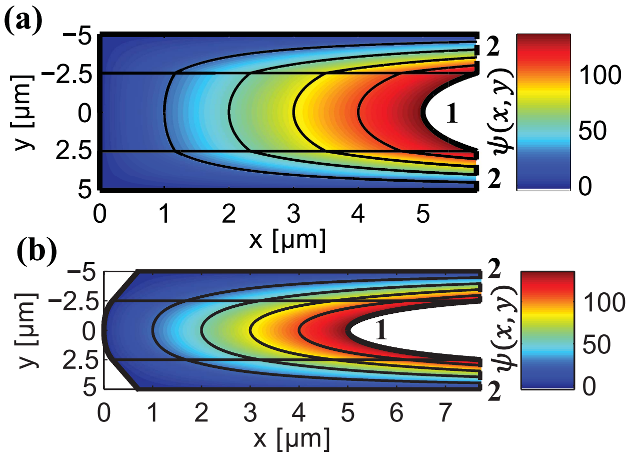

Fig. 4. Potential distribution $\psi(x, y)$ in a RESURF device with graded charge. (a) Dielectric RESURF ($\varepsilon_1 = 11.7\varepsilon_0$, $\varepsilon_2 = 3.9\varepsilon_0$, $\rho_1 = 1.5\ \mathrm{C/cm^4} \cdot x$, and $\rho_2 = 0$). (b) p-n junction RESURF ($\varepsilon_1 = \varepsilon_2 = 11.7\varepsilon_0$, $\rho_1 = 4.9\ \mathrm{C/cm^4} \cdot x$, and $\rho_2 = -0.32 \cdot 10^{-3}\ \mathrm{C/cm^3}$). Device dimensions: $t_1 = t_2 = 2.5\ \mu$m and $L = 5\ \mu$m. Boundary potentials: $V_{\mathrm{left}} = 0$ V, $V_{\mathrm{right1}} = \mathrm{BV} = 136.2$ V, and $V_{\mathrm{right2}} = 54.4\ \mathrm{V}/\mu\mathrm{m} \cdot (t_1 + t_2 - y)$ in (a) and $V_{\mathrm{right2}} = 1.5\ \mathrm{V}/\mu\mathrm{m}^2 \cdot (t_1 + t_2 - y)^2 + 50.6\ \mathrm{V}/\mu\mathrm{m} \cdot (t_1 + t_2 - y)$ in (b), $V_{\text{top-bottom}} = 0$ V.

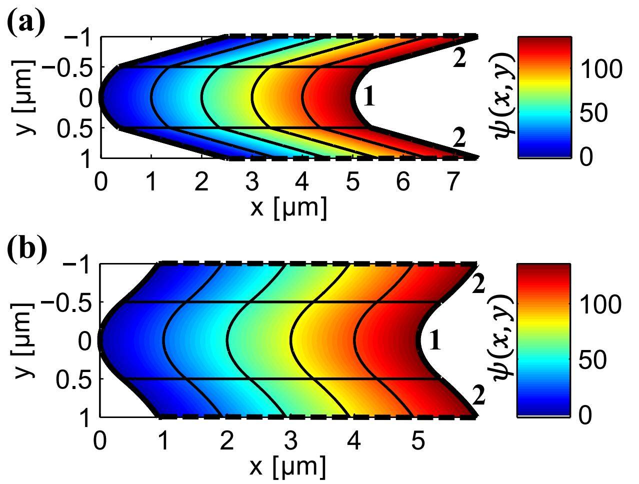

Fig. 5. Potential distribution $\psi(x, y)$ in a RESURF device with graded field plate potential. (a) Dielectric RESURF ($\varepsilon_1 = 11.7\varepsilon_0$, $\varepsilon_2 = 3.9\varepsilon_0$, $\rho_1 = 8 \cdot 10^{-3}\ \mathrm{C/cm^3}$, and $\rho_2 = 0$). (b) p-n junction RESURF ($\varepsilon_1 = \varepsilon_2 = 11.7\varepsilon_0$, $\rho_1 = 8 \cdot 10^{-3}\ \mathrm{C/cm^3}$, and $\rho_2 = -3.2 \cdot 10^{-3}\ \mathrm{C/cm^3}$). Device dimensions: $t_1 = t_2 = 0.5\ \mu$m and $L = 5\ \mu$m. Boundary potentials: $V_{\mathrm{left}} = 0$ V, $V_{\mathrm{right}} = \mathrm{BV} = 136.2$ V, and $V_{\text{top-bottom}} = 27.2\ \mathrm{V}/\mu\mathrm{m} \cdot (x - 2.5\ \mu\mathrm{m})$ in (a) and $V_{\text{top-bottom}} = 27.2\ \mathrm{V}/\mu\mathrm{m} \cdot (x - 0.93\ \mu\mathrm{m})$ in (b).

### B. Periodic RESURF

An example of periodic superjunction RESURF is shown in Fig. 7. As discussed in Step 4 of the procedure in Section III, no graded parameters are needed for ideal periodic RESURF. The charge densities $\rho_1$ and $\rho_2$, thicknesses, and field-plate potentials are, therefore, taken to be constant.

## IV. COMBINED RESURF STRUCTURES

Besides achieving ideal RESURF by grading one parameter or exploiting periodicity, one can also create

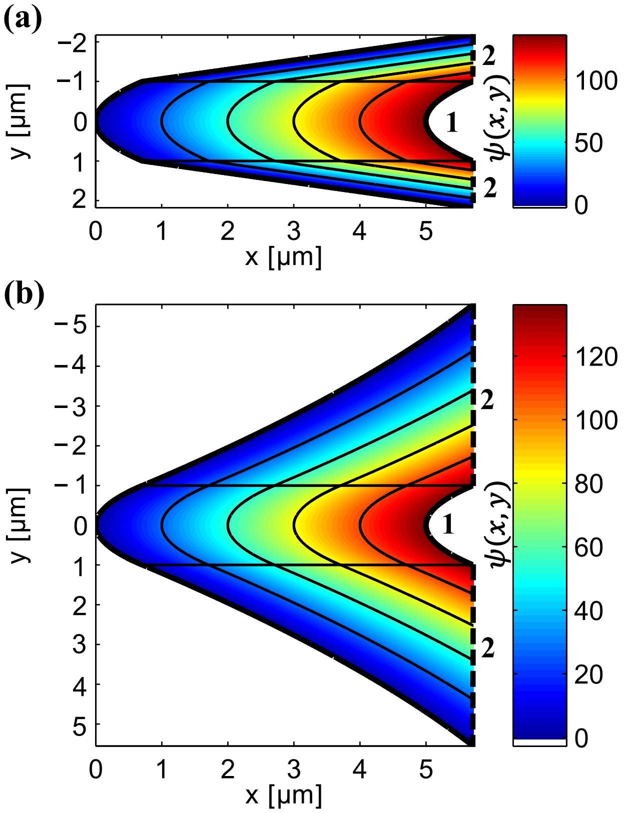

Fig. 6. Potential distribution $\psi(x, y)$ in a RESURF device with graded domain 2. (a) Dielectric RESURF ($\varepsilon_1 = 11.7\varepsilon_0$, $\varepsilon_2 = 3.9\varepsilon_0$, $\rho_1 = 0.4 \cdot 10^{-2}$ C/cm$^3$, and $\rho_2 = 0$). (b) p-n junction RESURF ($\varepsilon_1 = \varepsilon_2 = 11.7\varepsilon_0$, $\rho_1 = 0.4 \cdot 10^{-2}$ C/cm$^3$, and $\rho_2 = -0.4 \cdot 10^{-3}$ C/cm$^2$). Device dimensions: $t_1 = 1\ \mu$m, $t_2 = 0.24 \cdot (x - 0.71\ \mu\text{m})$ in (a) and $t_2 = 467.2\ \mu\text{m}^{-1} \cdot (x - 0.71\ \mu\text{m})^2 + 0.66 \cdot (x - 0.71\ \mu\text{m})$ in (b) and $L = 5\ \mu$m. Boundary potentials: $V_{\text{left}} = 0$ V, $V_{\text{right1}} = \text{BV} = 136.2$ V, and $V_{\text{right2}} = 126\ \text{V}/\mu\text{m} \cdot (t_1 + t_2 - y)$ in (a) and $V_{\text{right2}} = 1.94\ \text{V}/\mu\text{m}^2 \cdot (t_1 + t_2 - y)^2 + 21.2\ \text{V}/\mu\text{m} \cdot (t_1 + t_2 - y)$ in (b), $V_{\text{top-bottom}} = 0$ V.

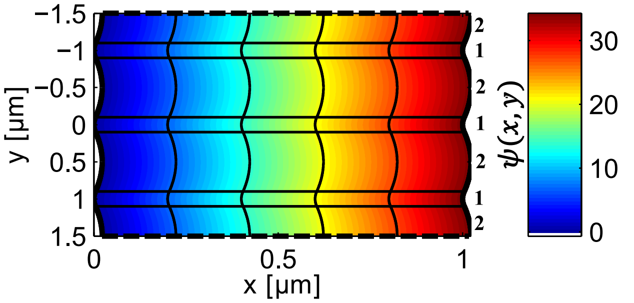

Fig. 7. Potential distribution $\psi(x, y)$ in a periodic superjunction RESURF device (three periods are shown). Device parameters: $\varepsilon_1 = \varepsilon_2 = 11.7\varepsilon_0$, $\rho_1 = 3.2 \cdot 10^{-3}$ C/cm$^3$, $\rho_2 = -8 \cdot 10^{-4}$ C/cm$^3$, and $L = 1\ \mu$m. Boundary potentials: $V_{\text{left}} = 0$ V, $V_{\text{right}} = \text{BV} = 34.2$ V, and $V_{\text{top,bottom}} = 34.2\ \text{V}/\mu\text{m} \cdot (x - 0.02\ \mu\text{m})$.

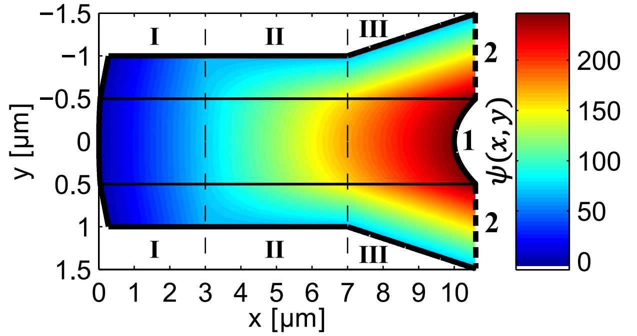

Fig. 8. Exact solution of the 2-D potential distribution $\psi(x, y)$ in a compound dielectric RESURF device consisting of three regions (I, II, and III). Region I ($L_{\text{I}} = 3\ \mu$m) has a linearly graded field-plate potential from $V_{\text{FP}} = 0$ V to $V_{\text{FP}} = 67.2$ V, $N_D = 5 \cdot 10^{15}$ cm$^{-3}$, and $t_1 = t_2 = 0.5\ \mu$m. Region II ($L_{\text{II}} = 4\ \mu$m) has a linearly graded doping from $N_D = 5 \cdot 10^{15}$ cm$^{-3}$ to $N_D = 7.8 \cdot 10^{16}$ cm$^{-3}$, $V_{\text{FP}} = 67.2$ V, and $t_1 = t_2 = 0.5\ \mu$m. Region III ($L_{\text{III}} = 3\ \mu$m) has a linearly graded domain 2 thickness from $t_2 = 0.5\ \mu$m to $t_2 = 1\ \mu$m, $t_1 = 0.5\ \mu$m, $N_D = 7.8 \cdot 10^{16}$ cm$^{-3}$, and $V_{\text{FP}} = 67.2$ V. Left–right boundary potentials: $V_{\text{left}} = 0$ V, $V_{\text{right1}} = \text{BV} = 246.7$ V, and $V_{\text{right2}} = 67.2\ \text{V} + 179.4\ \text{V}/\mu\text{m} \cdot (t_1 + t_2 - y)$.

combined devices. Combining different methods can be useful when the grading of only one parameter requires values that are difficult to achieve in real devices. Fig. 8 shows a semiconductor-dielectric structure (with $\rho_2 = 0$), where the graded-field plate, graded charge, and graded dielectric thickness methods have been combined. The compound device has been constructed by the methods discussed in Section III, making sure that the potential is continuous at the interfaces I–II and II–III. Thus, the device satisfies (1) and (2) throughout the 2-D region.

## V. DISCUSSION

In Section III, examples of ideal semiconductor-dielectric structures satisfying the RESURF condition have been shown. Deviations from ideal RESURF and other issues occurring in real devices are discussed in this section, which focuses on the shape of the boundaries (Section V-A), linearly graded potentials (Section V-B) and premature breakdown (Section V-C).

### *A. Effect of Deviations From Ideal RESURF on BV*

The curved design of the left and right boundaries needed for ideal RESURF increases the total device length along the $x$ axis. In Fulop's approximation [24] breakdown occurs at a critical field $E_{\text{crit}} = [1/(Af^1/7L^1/7)]$, where $A_f = 1.8 \cdot 10^{-35}$ cm$^6$/V$^7$ is the silicon ionization coefficient, and $L$ is the device length. The BV of an ideal device with curved boundaries is then $\text{BV}_{\text{curved}} = E_{\text{crit}} L = (L^{6/7}/A_f^{1/7})$. If the device has straight boundaries, however, for the same length $L$, the device will have a lower BV, because the boundaries do not have the ideal shape. The BV with straight boundaries is given by $\text{BV}_{\text{straight}} = \eta \text{BV}_{\text{curved}}$, where $\eta = (\text{BV}_{\text{straight}}/\text{BV}_{\text{curved}})$ is defined as the ratio of BVs of a device with straight boundaries and that of a device with ideally curved boundaries with the same length $L$. The parameter $\eta$ depends on the device length, geometry, and doping profile and can be extracted in simulations by calculating the ionization integral along the symmetry line at $y = 0$ (where the $E_x$ field is maximum). In Fig. 9, $\eta$ is shown for a device with graded field-plate voltage and $\rho_2 = 0$ as a function of the length $L$ for different values of the fixed charge $\rho_1$ in Fig. 9(a) and of the equivalent thickness $t_{\text{eq}}$ in Fig. 9(b). It can be seen that $\eta$ reduces for increasing $\rho_1$ and for increasing thicknesses $t_{\text{eq}}$ (assuming $t_1 = t_2$). The reduced values of $\eta$ in these cases are

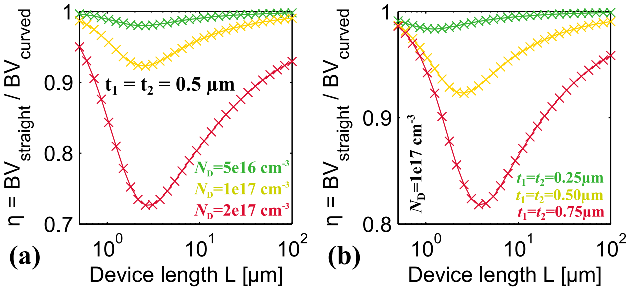

Fig. 9. Ratio between the straight and the curved $E_x$ BV [$\eta = (\mathrm{BV}_{\mathrm{straight}}/\mathrm{BV}_{\mathrm{curved}})$] for a dielectric RESURF device with graded field-plate potential, as in Fig. 5(a), having (a) different doping charges $\rho_1 = qN_D$ and (b) different thicknesses $t_{\mathrm{eq}}$ (with $t_1 = t_2$).

caused by the more pronounced curvature of the equipotential lines, which increases the difference between the curved and straight device designs and the BV. As the device length increases, $\eta$ approaches unity, because boundary-shape-related effects become less significant for $L \gg t_1$. The value of $\eta$ is also close for very short devices, since in the limit of $t_1 \gg L$, the electric field will behave as in a parallel plate capacitor, and the effect of curvature on BV becomes small. As a result, for the simulated devices in Fig. 9, the parameter $\eta$ reaches a minimum for a device length $L \approx 1$–$5$ $\mu$m.

### *B. Boundary Conditions With Graded Potential*

In non-periodic devices, a gradient is needed to achieve the optimal RESURF condition using the methods shown in Section III. Grading the potential at the field plate and dielectric boundaries and/or at the left and right boundaries is possible. In practice, graded boundary potentials are not easily implemented. A possibility is to split the graded potential in a number of constant voltage field plates [25], or to use conductive resistive elements [26]. It is also possible to exploit structural symmetries to achieve a graded potential on a boundary without a field plate. For example, the periodicity in the $y$-direction is exploited in superjunctions resulting in the charge balance condition (9). Similarly, a symmetric design around the $x = L$ line can be used to mimic a linearly graded potential on the right boundary.

### *C. Junction, Vertical, and Dielectric Breakdown*

Besides breakdown caused by the $E_x$ field, device breakdown might also be caused by the $E_y$ field [15]. In order to arrive at an optimized device design, it is, therefore, necessary to design the RESURF device, such that the ionization integral along the electric field lines in the $y$-direction at $x = L$ does not exceed unity. Using the Fulop's approximation [24], this condition yields

$$\rho_1(x = L) \cdot t_1(x = L)^{7/8} \le \left(\frac{8}{A_f}\right)^{1/8} \varepsilon_1^{7/8} \qquad (12)$$

with $A_f = 1.8 \cdot 10^{-35}$ cm$^6$/V$^7$ in silicon. In addition, avalanche breakdown of the p-n junction comprising the p-well (for an nMOS) of the power transistor and the drift extension has to be considered. As shown in [15], the condition $N_D(x = 0) \cdot t_1 \le 10^{12}$ cm$^{-2}$ [12] limiting the RESURF dose at $x = 0$ can be used for this purpose in silicon-based devices. In the presence of dielectrics, the magnitude of the electric field should not exceed the critical value for dielectric breakdown. Finally, it is worth mentioning that for electric field magnitudes exceeding 70 (V/$\mu$m) in silicon band-to-band tunneling also limits the BV [17], [27].

## VI. CONCLUSION

In this paper, 2-D analytical solutions of Poisson's equation have been derived that satisfy the ideal RESURF condition (1). Several examples of how these solutions can be used for ideally shaping the geometry of field-plate and periodic RESURF devices have been demonstrated. The analytical solutions provide insight in the physics and facilitate device optimization. The different geometry shaping procedures demonstrate the degrees of freedom available for optimizing RESURF devices. Moreover, the derivation of the shape of idealized structures allows the analysis of deviations from the ideal shape in practical devices. For instance, it is shown that devices with curved boundaries can have a higher breakdown than devices with straight boundaries. With sufficient technological control over device dimensions and doping profiles, the demonstrated device geometries with curved boundaries and field plates can lead to optimized RESURF drift extensions.

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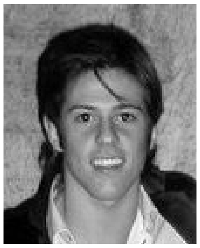

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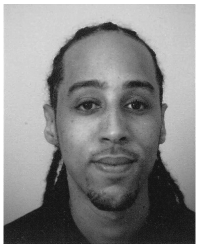

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