Semiconductor devices with modulation of electrode's area

V.M. Ioffe

Abstract - This work presents some new semiconductor devices based on the principle of modulation of electrode's area.
The principle of modulation of electrode's area (MEA) allows to improve essentially characteristics of some existing semiconductor devices and to design some new devices. The MEA principle can be used in semiconductor structures with area surface's nonuniform physics properties (impurity distribution, permittivity, semiconductor film's depth).

1. **The MEA varactors**

The MEA varactors are proposed with arbitrary predetermined form of C(V) characteristic and superhigh (~ 10^2 -10^4) Cmax/Cmin relation.

The standard varactor's structure is a semiconductor film on a heavily douped substrate with opposite type of conductivity. The film and substrate have contacts to apply an external voltage. A main carrier's depletion layer is formed in the semiconductor under the certain polarity of a bias voltage. The depletion layer depth (equivalent to an insulating layer in a capacitor) depends on the bias voltage and the impurity distribution in a film.

Lacks of the standard design:

1. It is impossible to realize an arbitrary predetermined C(V) characteristic because of two reasons: (a) technological complexity of formation a structure with predetermined impurity distribution in the film and (b) impossibility of realization some practically important C(V) by means of any real impurity distribution.

2. The minimum value of varactor's capacitance depends on a breakdown voltage.

The standard varactor is equivalent to the capacitor with varying capacitance by change a distance between plates by means of the bias voltage. To eliminate limitations of standard varactors a new MEA varactor structures are proposed. In those structures the distance between capacitor's plates and the plate's area both are changed simultaneously with bias voltage. The MEA principle easily allows to realize arbitrary C(V) characteristic on practice.

Fig.1. shows one of some variants of the proposed MEA varactors. The p+ type substrate has an ohmic contact. The n-type film (with depth D) has an ohmic contact formed as a line on perimeter of the working region of the film. In the film's working region ($0<x<X_{max}, 0<z<F(x)$) there is a nonuniform donor's profile Ni(x,y) created by ion-implantation doping (implantation dose is increased from Xmax to 0). Outside a working region the film is lowly doped and fully depleted by main carriers if the bias voltage on a junction is zero. The space charge region(SCR) gradually fills the film's working region with increasing of back bias voltage. So a neutral region size H(V) and an effective capacitor's plate area S both are decreased continuously:

$$S = \int_0^{H(V)} F(x)dx + Sk$$

Where Sk - is the ohmic contact area over the SCR. For realization of necessary C(V) characteristic in proposed structure it is possible to vary three parameters F (x), D (x), Ni (x, y) as each separately and all together, unlike the standard varactor structure with C(V) depending on Ni(x,y) only. So the complex technical problem of specified doping profile formation is replaced by a simple problem of specified deposition mask formation.

The lack of the described structure - low merit factor because of large neutral region volume resistance is eliminated by means of high conductive strips fabricated along z- direction with gap past contact line on the working region film's surface (Fig.2).

To eliminate undesirable influence of the surface an isolator layer (SiO_2) can be formed on it. The isolator can be carried out also as a p-n junction.

To achieve a maximum capacitance span ratio it is necessary to minimize the contact area Sk and to remove a contact platform (which can be large sizes) on the SiO_2 layer.

Varactor's C(V) characteristic is determined by equation:

$$C(U) = \varepsilon_s \int_0^{H(V)} (F(x)/R(x,V))dx \qquad (1)$$

H(V) is determined from condition: D(H)= R (x, V). R (x, V) is determined from equation:

$$V + Vk = q/\varepsilon_s \int_0^{R} Ni(x,y)ydy \qquad (2)$$

Where R(x,V)-SCR depth, H(V)-neutral region size in x-direction, ε_s - semiconductor permittivity, Vk - barrier built-in potential.

Linear varactors particularly used as multiplying or parametric diodes are of great interest. It's because an average capacitance of the linear varactor is not a function of a harmonic signal level. So there is no detuning in resonant circuits using these varactors. Fig.3. shows a calculated form of film's working region for varactor with linear C(V) characteristic (C(V)~1-V/Vmax). Such a varactor is fabricated by phosphorus ion implantation (energy 200 keV) in a lowly doped n-type Si film (0.6 mcm depth) with linearly decreasing implantation dose along x (from 10^{12} to 1.54 10^{11} ion/cm^2).

Now we estimate the merit factor Q of varactor without high conductive strips (Fig.1) neglecting a constant current of the p-n junction. In this case Q is the ratio of varactor capacitor resistance to volume resistance R. If H(V)>>F then:

$$Q = 1 / (\omega C R); \; R \approx F\rho / (D\, H (V)).$$

Where D - an average thickness of the film, H (V) - a neutral region size in x-direction , F - an average value of F (x) on interval $0 \le x \le H$ (V), ρ - an average specific resistance of a film in the neutral region, ω - an angular frequency,

$$C \approx \varepsilon_s (F\; H(V) / D + Sk / D).$$

If Sk << FH (V) then

$$Q \approx (D / F)^2 / (\varepsilon_s\; \rho\; \omega).$$

Similarly, if F>>H (V) then

$$Q \approx (D/ H(V))^2 / (\varepsilon_s\; \rho\; \omega).$$

Now we consider a case when H (V) >> F at presence of high conductive strips :

$$R \approx \rho\, \Delta\; / (D\, H(V)).$$

Where Δ - size of a gap between strips and a contact line. Then

$$Q \approx D^2 / (\varepsilon_s\; F\, \Delta\, \rho\, \omega).$$

So a presence of conducting strips results in increasing of Q in F/Δ of time.

We consider below other examples interesting for practical applications.

The MEA varactor with uniform film.

The working region of a film can be uniformly doped along x-direction and to have similar thickness in that case, when the semiconductor substrate forming a p-n junction with a film is nonuniformly doped in õ-direction (Fig.4). The doping of a substrate is increased along x-direction within the working region and outside it the substrate is strongly doped. The SCR thickness in the substrate is decreased monotonously with õ and so the SCR thickness in the film is increased with õ. The SCR gradually fills the whole working region of a film with increasing of a back bias voltage on the varactor. Thus an effective area of the condenser's plates is continuously decreased. Equations describing varactor if the substrate and the film are made of one semiconductor material by analogy with (1) and (2) look as follows:

$$C(V) = \varepsilon_s \int_0^{H(V)} \frac{F(x)}{R(x,V)} dx\,.$$

$$V + Vk = q/\varepsilon_s \int_0^{R1} Nd(x,y)ydy + q/\varepsilon_s \int_0^{R2} Na(x,y)ydy$$

And the equation of electrical neutrality for semiconductor is:

$$\int_0^{R1} Nd(x,y)dy = \int_0^{R2} Na(x,y)dy$$

R= R1 + R2
H (V) = x at R1=D .

Here R1, R2 - SCR thickness in the film and in the substrate, Na (x, y) - impurity distribution in the substrate, Nd (x, y) - impurity distribution in the film.

The calculated C(V) characteristics are presented in Fig.5 for varactors with uniformly doped 0.5 micron silicon film having donor concentration 10^{16} cm^{-3} and with nonuniformly doped substrate having acceptor concentration linearly varying in the working region from 10^{15} to 10^{16} cm^{-3}. Characteristics are presented for various forms of working regions: two triangular (F (x) = 1-x/Xmax, F (x) = x/Xmax (mm)) and rectangular (F (x) = 0.5 mm). At Xmax= 1 mm Ñmax is equal to 105 pF.

The MEA varactor formed as a periodic structure

The variable parameter is a thickness of the film. Varactor is formed from a uniformly doped semiconductor as a shape of periodic structure (Fig.6) with a Schottky barrier on the top surface and an ohmic contact on the bottom . The calculated form of periodic structure section is presented on Fig.7 for the MEA varactor with linear C(V) characteristic. The structure is formed with an anisotropic etching of silicon.

The MEA varactor with a film formed as a shape of a wedge

The variable parameter is F(x). Varactor is formed from a uniformly doped semiconductor film as a shape of a wedge placed on substrate with opposite type of conductivity (Fig.8). The forms of working region of a film for various C(V) characteristics ($C(V) \sim (1-V/Vmax)^n$, n=1,2,3, $Vmax= q\, Ni\, Dmax^2/2\varepsilon_s - Vk$, Dmax - maximum thickness of a wedge) are presented in Fig. 9. The wedge is formed with an anisotropic etching of the semiconductor oriented by an appropriate manner.

2. The MEA capacitance transformer

The proposed MEA capacitance transformer permits to vary a capacitance by a voltage on other capacitor.

As an example we consider the MEA capacitance transformer which contains p-n junction (Schottky barrier) with non-uniform doping profile along x-direction. The insulator layer 1 is formed on a the p-n junction (Schottky barrier) surface and the metal layer 2 is formed on insulator surface (Fig. 10). The p-n junction contains a heavily doped p+ region with an ohmic contact and n-type film with other ohmic contact. The film is nonuniformly doped (donor concentration is increased from Xmax to 0). The SCR gradually fills the whole film with increasing of a back bias voltage on the junction. Thus a neutral region size H(V) and effective area of plates of the controlled capacitor (formed between neutral region and metal layer 2) are continuously decreased. If C(t) is dependence of capacitance of controlled capacitor on time and Q is the charge on controlled capacitor then a voltage on controlled capacitor is $V_2 = Q/C(t)$.

The parametric amplifier with direct voltage power source.

A large direct voltage power source is connected through the load to the MEA capacitance transformer (Fig.11). An opportunity is used to change a capacitance between a film's ohmic contact and metal layer 2 by means of comparatively small voltage on p-n junction. The calculated time dependence of voltage on controlled capacitor of its percentage modulation is presented on Fig.12.

The MEA capacitance transformer with conductive strips

The MEA capacitance transformer is with p-n junction (Schottky barrier) having nonuniform doping along x-direction. The p-n junction containing a heavily doped p+ region with an ohmic contact and n-type film with other ohmic contact is carried out above conductive strips 3. The conductive strips are formed on one surface of insulator. On other insulator surface a metal layer 2 is formed (Fig.13). The conductive strips are carried out on working region ($0 \le x \le Xmax$, $0 \le z \le F(x)$). A nonuniform donor impurity profile Ni(x,y) is created in the film by ionic doping. An implantation dose is increased from Xmax to 0. The SCR gradually fills the film working region with increasing of a back bias voltage on the junction. Thus a neutral region size H(V) and effective area of plates of the controlled capacitor (formed between conductive strips 3 and metal layer 2) are continuously decreased. For exception of undesirable influence of capacitor coupling between region 2 and p + region the p-n junction (Schottky barrier) is formed above insignificant part of strips 3. With a choice of the working region form F(x) it is possible to produce a necessary C(V) dependence determined by an equation:

$$C(V) = C\min + \varepsilon_s / D \int_0^{H(V)} F(x)dx$$

where the Cmin is determined by the n-film's ohmic contact sizes.

Fig.14 shows a calculated dependence of the working region form for controlled capacitor that can be used in the LC circuit as an ideal frequency modulator ($C(V) = C_1/(C_2 + V)^2$) with Cmax/Cmin=5. The doping level in n-region is linearly falling down along x-directions (H (V) ~ Xmax (1-V/Vmax)).

By epiplanar technology of semi-conductor devices all contacts, as a rule, are formed on one surface of a semi-conductor plate, and the contacts are separated by an insulator layer (SiO_2). The controlled capacitor carried out by means of epiplanar technology is presented on Fig.15. The capacitor contains conducting strips -3, conducting site -6, insulator layer -5 , nonuniformly doped along device width n-type region -1 with ohmic contact, region -2 (with ohmic contact) which forms p-n junction with region -1. On Fig.15 are represented also a source of a control voltage - 9 connected to p-n junction and a source of an input signal -10. The strips 3 are carried out from alloy of gold and antimony (to form an ohmic contact to n-type semiconductor). SiO_2 is used as insulator. An ohmic contact to p-range 2 , an ohmic contact to n-range 1 and the site 6 are carried from aluminium. All the contacts are separated with each other by a SiO_2 field oxide layer -8.

The MEA capacitance transformers can be used for constructing high-power generators, amplifiers and modulators because they have no restrictions of other semiconductor devices (transistors, diodes) connected with electric breakdown of the sufficiently thin p-n junction SCR.

3. The MEA voltage controlled transmission lines

The main lack of all transmission lines is a fact that parameters of a line such as the wave resistance and the length are not controlled by an external voltage source. That fact complicates frequency tuning and changing for many microwave devices.

The MEA voltage controlled transmission line is presented in Fig.16. The MEA line contains conducting strips (carried out along length of line) -3, conducting site - 6, insulator layer -5, n-type region -1 nonuniformly doped along width of a line and having ohmic contact, p+ - type range -2 (with ohmic contact) forming p-n junction or Schottky barrier with range 1. There are also presented a source of control voltage - 9 connected to p-n junction through inductance -11 (for ac decoupling) and a source of an input signal -10. A layer of n-type polycrystalline silicon 1 is produced above the conducting strips 3 and forms an ohmic contact with strips. The layer is nonuniformly doped along a line width (z-direction). The doping level is decreased with increasing of z. The neutral region size H (V) along z-direction in n-type semiconductor is continuously decreased with increasing of a back bias voltage (by the source 9) on the p-n junction. Thus an effective line width W repeats H(V) with step equal to width of one strip 3 , and so the line wave resistance is proportionally increased (ρ ~ 1/ H (V)).

The MEA voltage controlled transmission line with variable length is presented in Fig.17. The MEA line contains conducting strips -3 (carried out along width of line), conducting site - 6, insulator layer -5, n-type region -1 nonuniformly doped along length of line and having an ohmic contact, p+ - type range -2 (with an ohmic contact) forming p-n junction or Schottky barrier with a range 1. There are also presented a source of control voltage - 9 connected to p-n junction through inductance -11 (for ac decoupling) and a source of an input signal -10. A layer of n-type polycrystalline silicon 1 is produced above the conducting strips 3 and forms an ohmic contact with strips. The layer is nonuniformly doped along line length (x-direction). The doping level is decreased with increasing of x. The neutral region size H(V) along x-direction in n-type semiconductor is continuously decreased with increasing of a back bias voltage (by the source 9) on the p-n junction. Thus an effective length L of line repeats H(V) with step equal to width of one strip 3.

For exception of undesirable influence of a capacitor coupling between regions 6 and 2 a p-n junction (Schottky barrier) can be formed above part of strips 3. The MEA line is presented in Fig.18. The line contains conducting strips -3 (carried out along line length), conducting site -6, insulator layer -5, n-type region -1 nonuniformly doped along width of line and having an ohmic contact, p+ - type range -2 (with an ohmic contact) forming p-n junction or Schottky barrier with a range 1. There are also presented a source of control voltage - 9 connected to p-n junction through inductance -11 (for ac decoupling), a source of an input signal -10, the resistance 12, connected to the line output. The p-n junction (Schottky barrier) is carried out in the beginning and at the end of line. We notice that p-n junction or Schottky barrier can be formed on continuation of conducting strips 3 outside the layer 5.

The second way for exception of undesirable influence of a capacitor coupling between regions 6 and 2 is a nonuniformly doping along z(x)- direction both in n- and p- regions of the p-n junction. Thus a neutral range size will be decreased along z(x)-direction both in n- and p-regions with controlled voltage increasing.

4. The MEA transistors

One of variants of a MEA device working as a transistor is presented in Fig.19. In this case the layer

5 should have conductivity. It can be a small thickness insulator (for tunnel current) or conductor including semiconductor material. A conductivity of the material should be enough low not to shunt region 1 of p-n junction (Schottky barrier).

The MEA structure contains n-type region -1(with an ohmic contact) nonuniformly doped along x-direction, region 2(with ohmic contact) forming a p-n junction or a Schottky barrier with region 1, conducting strips - 3, a layer - 5 carried out from weakly doped n-type semiconductor, conducting site -6. There are also presented a source of control voltage - 9 connected to p-n junction and source of direct voltage -13.

A layer of n-type silicon 1 is produced above the conducting strips 3 and forms an ohmic contact with strips. The layer is nonuniformly doped along x-direction. The doping level is decreased with increasing of x. The region 2 is produced above the silicon layer and forms a p-n junction or Schottky barrier with region 1. The neutral region size H(V) along x-direction in n-type semiconductor is continuously decreased with increasing of a back bias voltage (by the source 9) on the p-n junction. Thus an effective width W of ohmic contact (with range 1) repeats H(V) with step equal to width of one strip 3.

The conducting strips in analyzing structure (Fig.19) are formed only on one surface of a low conducting layer 5. If on the other surface to form the strips with nonuniformly doped p-n junction above (across the strips) it will be possible to vary an effective contact area by varying a voltage on the junction.

We have to notice that voltage dependence of the device resistance (between the ohmic contact and the site 6) is determined by a choice of the form of a region on which the conducting strips 3 are carried out and the doping profile of the p-n junction (Schottky barrier). If a change of the device resistance is required in a large limits and the size of the contact platform to the region 1 is comparable with device sizes the contact platform can be removed to a formed insulator layer. If it is not required to change resistance in a large limits the conducting strips 3 (carried out on a surface of the region 1) may be directly joined with the ohmic contact to region 1. In this case an effective area of contacts of the controlled resistor is changed of size equal to the area of gaps between strips 3.

The MEA transistors with high input and output resistance and arbitrary (including a linear) transfer characteristic

A transistor amplifier presented in Fig.20 contains a MEA transistor structure, a source of input voltage - 5,a direct bias source to emitter and base - 6,a back bias source to collector and base - 7, a resistance - 8. The MEA transistor structure contains four regions with ohmic contacts: n-type collector - 1, p-type base - 2, n-type emitter - 3, p-type control electrode.

The emitter range is nonuniformly doped along surface x-coordinate. A control electrode is formed above the emitter forming in working region ($0 \le x \le x_0$, $0 \le z \le F(x)$, $0 \le y \le D$)), and is made of opposite type semiconductor material to emitter (with ohmic contact to it) or from metal forming a Schottky barrier with emitter. And the doping level grows from $Õ_O$ to 0. The doping level and the film thickness are selected so that at least the part of working region is completely released from main carriers with applying a blocking voltage to the control electrode - emitter junction up to a breakdown. In accordance with increasing of blocking voltage V on the control electrode-emitter junction the x-size of neutral region H(V) and the effective area of the emitter S(V) are continuously decreased and results a proportional decreasing of emitter and collector currents (Iê ~ S (V)) and a signal on resistor 8 (in output). Thus the functional dependence of emitter and collector currents from voltage is determined by functional dependence of the emitter region size F (x) along z-direction

$$S(V) = \int_0^{H(V)} (F(x)dx \qquad (3)$$

(õ, z- are rectangular coordinates in plane of the emitter surface).

So the collector I(V) characteristic can be changed by setting of the emitter region form. The similar change of the emitter effective area can be achieved by surface uniform emitter doping with nonuniform emitter thickness and also by nonuniform thickness and nonuniform doping along surface x-coordinate. For the predominance of the emitter current over the base current a predominance of the emitter doping degree over the base doping degree is necessary. Or the emitter region must be wide-band-gap and the base region must be narrow-band-gap.

The MEA transistor with heavily doped strips in emitter

The MEA transistor is presented on Fig.21 and Fig.22. A large number of heavily doped strips 10 are formed in the nonuniformly weakly doped emitter range to increase the emitter efficiency. The strips 10 are formed with clearance to ohmic contact 9. The high conductive range 9 is formed to decrease an emitter volume resistance. The transistor operation does not differ from presented above. In accordance with increasing of blocking voltage V on the control electrode-emitter junction the x-size of neutral region of weakly doped emitter range is continuously decreased. So a heavily doped strips 10 inside the space charge range are separated from emitter.

All the transistor contacts are separated by an insulator layer 12 (SiO_2).

Such a transistor design permits:

1. To expand a range of applying voltage (an electric breakdown of thick weakly doped junction comes at essentially large voltage than of heavily doped).
2. To decrease the control electrode - emitter capacitance by forming of more thicker emitters.
3. To decrease the emitter volume resistance.

We shall notice that it is possible to achieve a change of the emitter effective area with the uniformly doped emitter. For this purpose it is necessary to use a control electrodes nonuniformly doped along õ-direction.

By choice of the emitter form it is possible to produce any transfer characteristic of the MEA transistor. Now we obtain the emitter form for linear MEA transistor. We suppose that a weakly doped emitter range has a more lower concentration than a base range. Neglecting a base voltage drop the overlapping voltage V (a minimum external voltage on control electrode-emitter junction leading to full depletion of emitter by majority carriers in section H(V)) can be written:

$$V+V_k+V_{k2}-V_2 = q/\varepsilon_s \int_0^{D(H(V))} Ni(H(V),y)\, y\, dy \quad (4)$$

V_2 - external voltage between base and emitter, V_{k2} - built-in potential of emitter - base junction, V_k - built-in potential of control electrode - emitter junction.

We present solutions of (3,4) for the linear dependence S(V):

a) for uniformly doped emitter range and linearly varied emitter thickness D (x) ~ xo-x, integrating (4) we obtain:

$V + V_k + V_{k2} - V_2 \sim (xo - x)^2$.

Linear changes of voltage should lead to linear decrease of the effective area:

DV ~ - (xo- x)= -F(x)dx, F(x)= -dV/dx ~ xo - x .

In this case we have a triangular form of the emitter area.

b) for uniform film depth (D(x)=D) and linearly decreased implantation doze along x-direction we obtain

$V + V_k + V_{k2} - V_2 \sim xo - x$.

For linear transistor we have:

DV ~ - 1= - F (x) dx, F (x) = - dV/dx ~ 1 .

In this case we have a rectangular form of the emitter area.

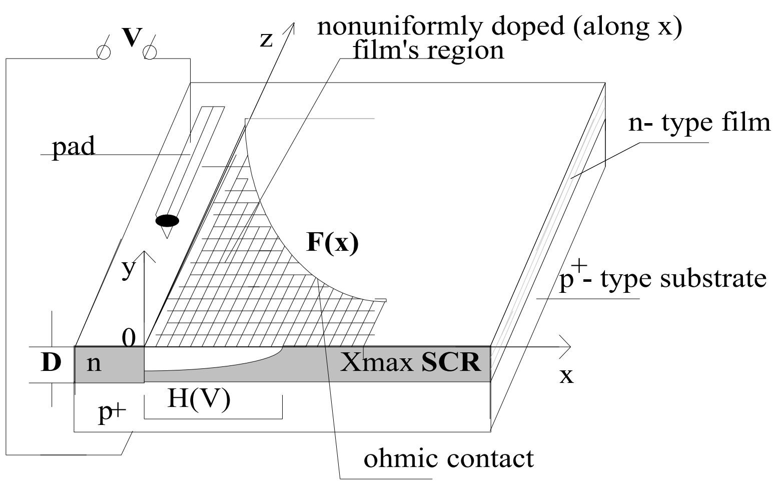

Fig. 1. The MEA varactor

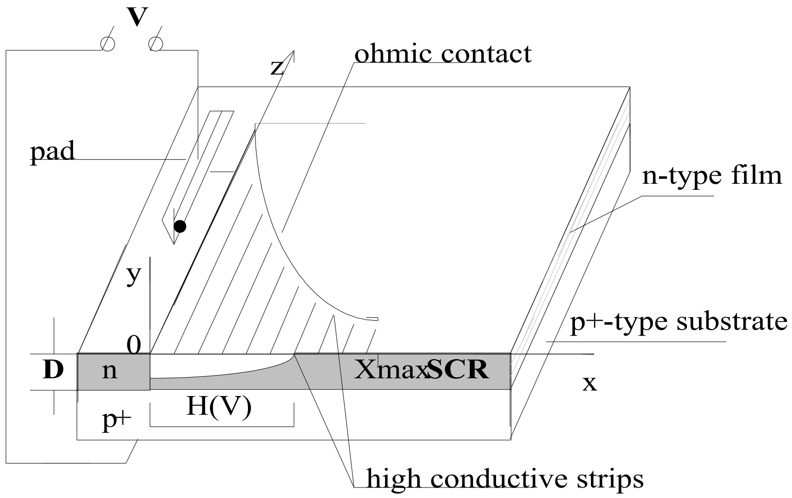

Fig. 2. The MEA varactor with high conductive strips

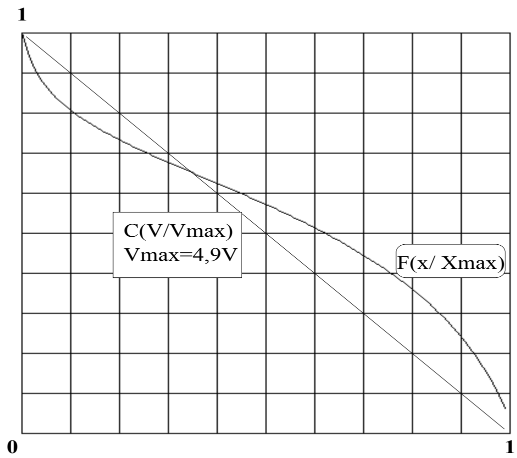

Fig.3. The calculated form of a film's working region for the MEA varactor with lineal C(V) characteristic

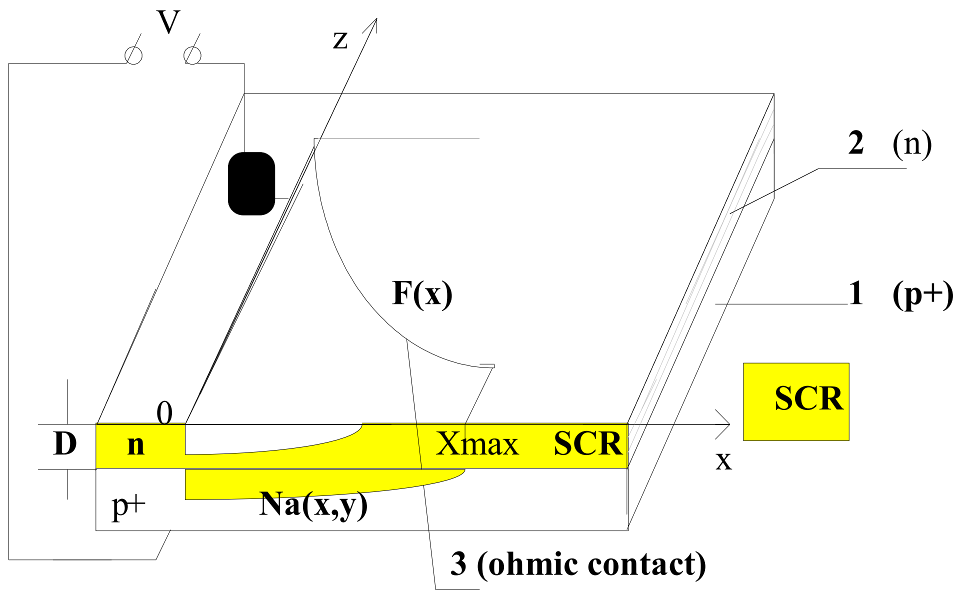

Fig.4. The MEA varactor with uniform film

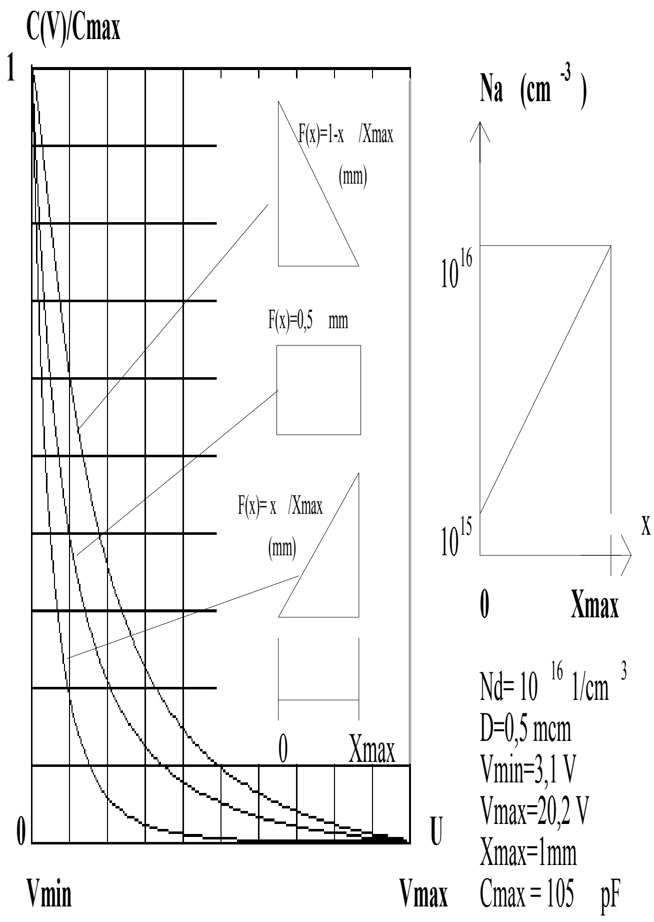

Fig.5. The calculated C(V) characteristics for the MEA varactors with uniform film and various form of working region

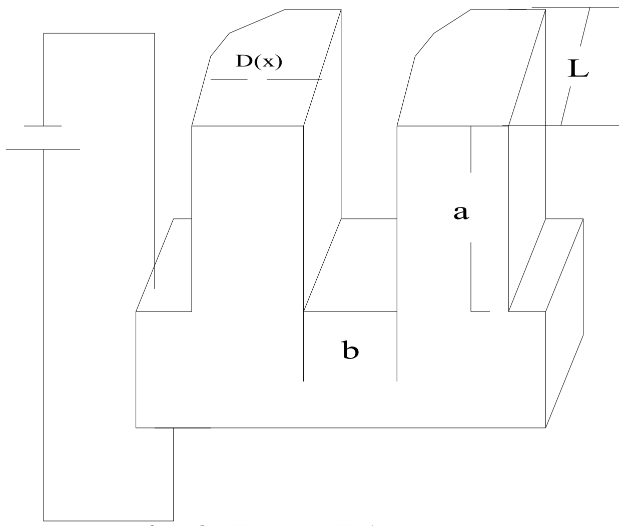

Fig.6. The MEA varactor formed as a periodic structure

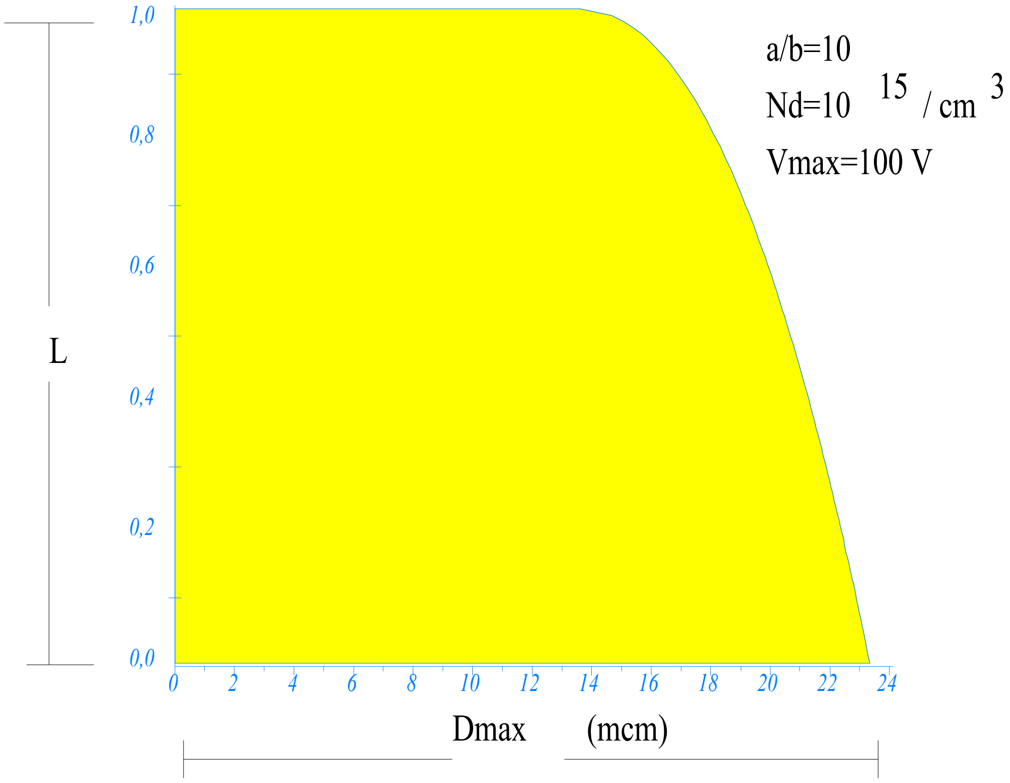

Fig.7. The calculated form of periodic structure section for the MEA varactor with linear C(V) characteristic

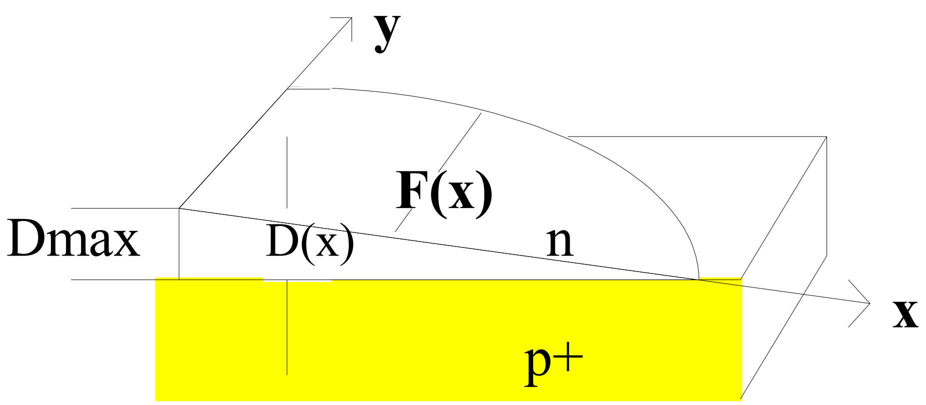

Fig.8. The MEA varactor with a film formed as a shape of a wedge

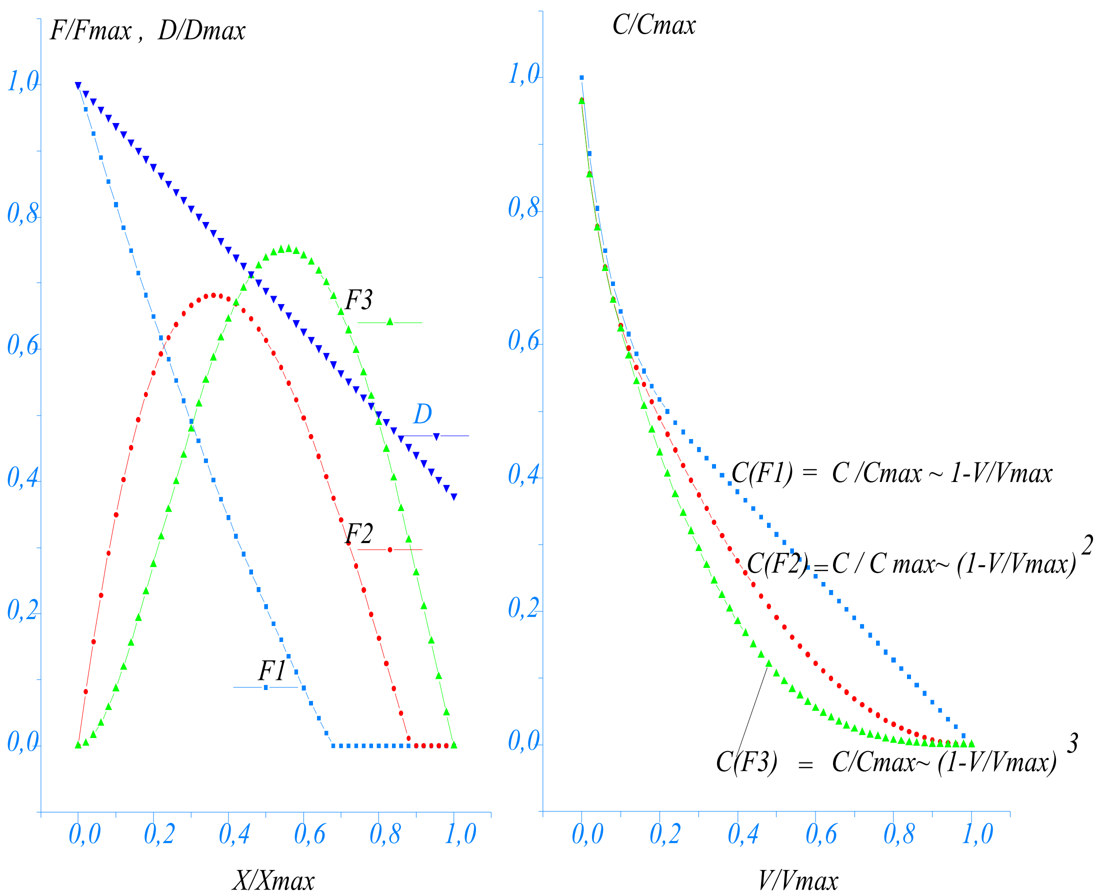

Fig.9. The forms of a working region of a wedge-shaped film for the MEA varactors with various C(V) characteristic

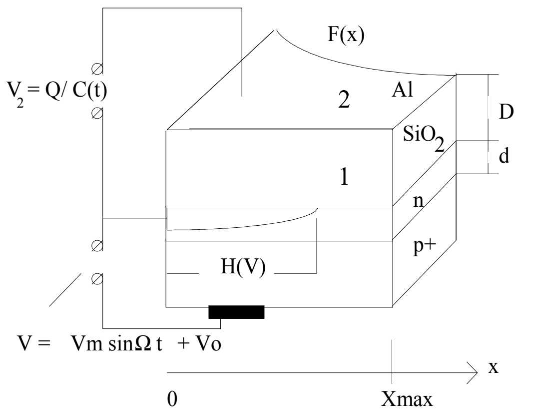

Fig.10. The MEA capacitance transformer

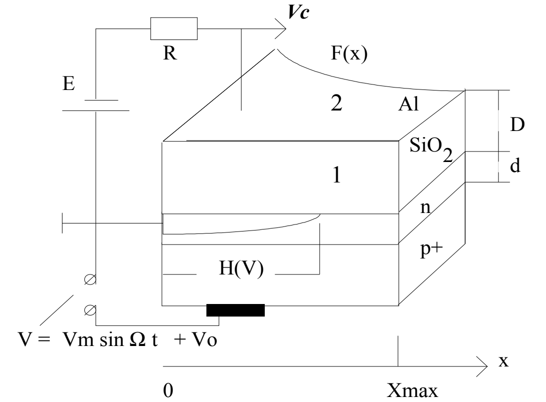

Fig.11. The amplifier with the MEA capacitance transformer

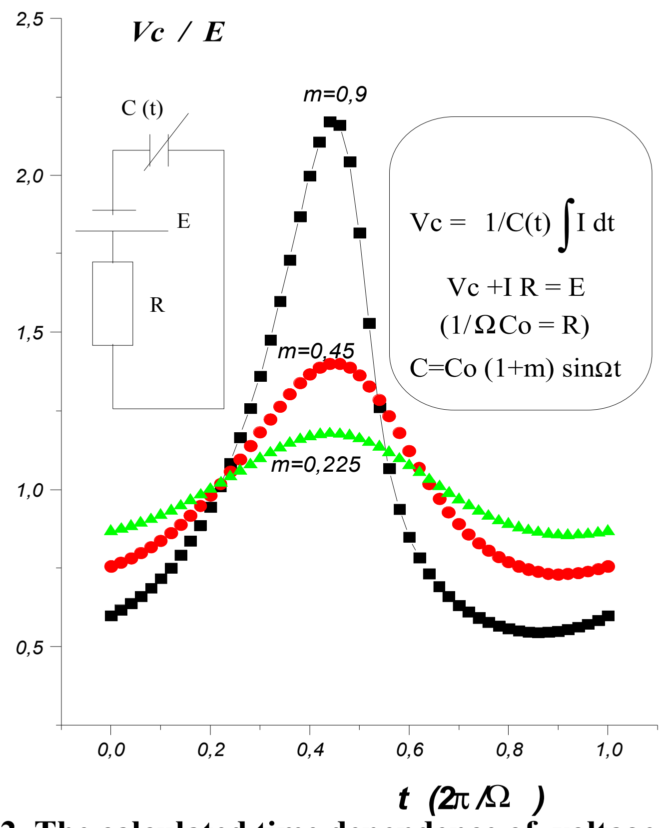

Fig.12. The calculated time dependence of voltage on controlled capacitor of its percentage modulation

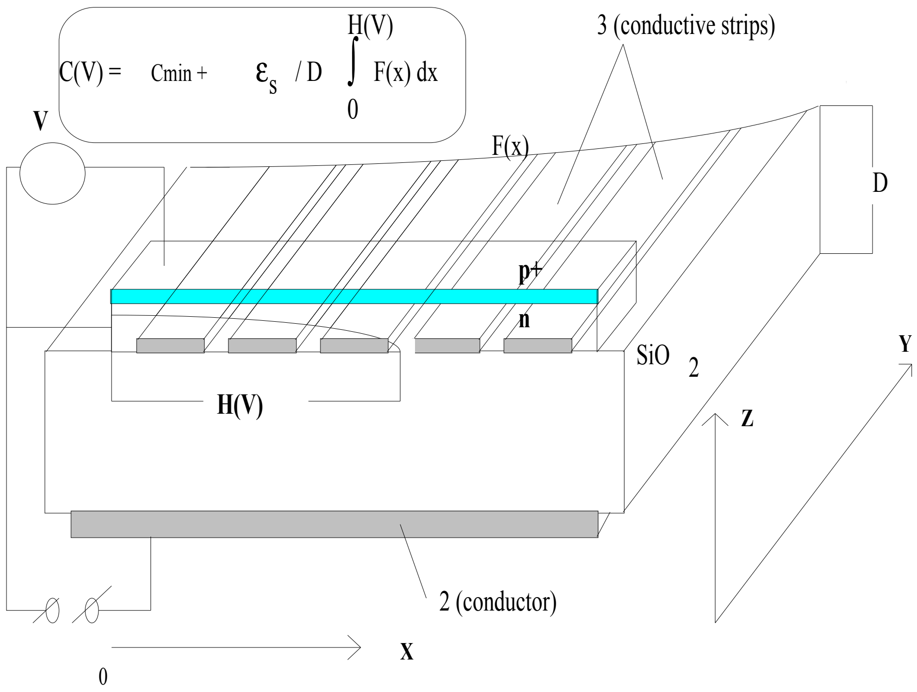

Fig.13. The MEA capacitance transformer with conductive strips

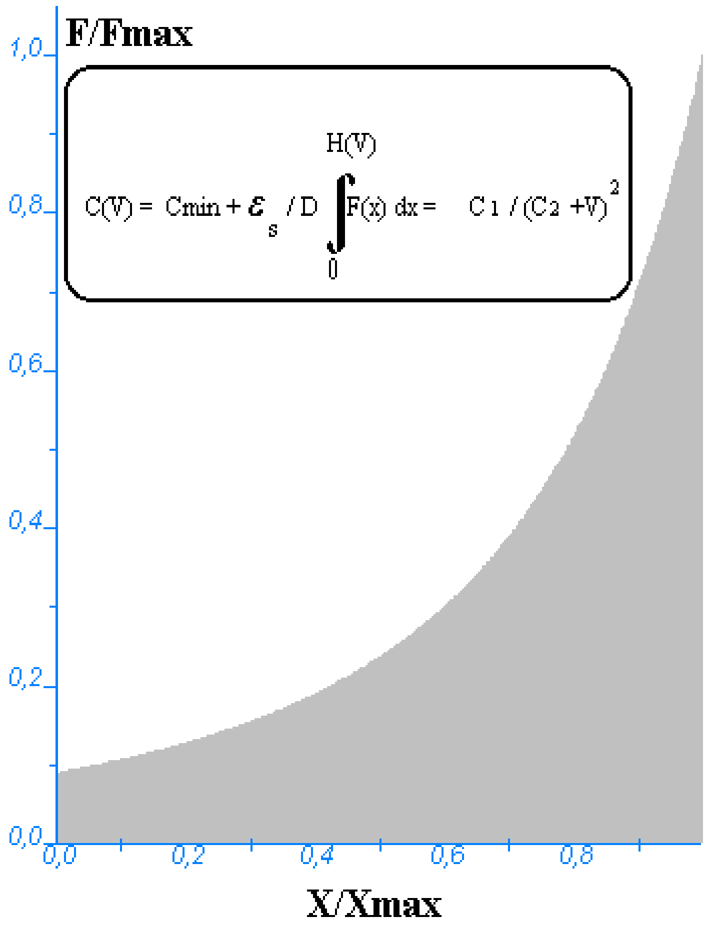

Fig. 14

Fig.14. The calculated working region form of controlled capacitor for ideal frequency modulator

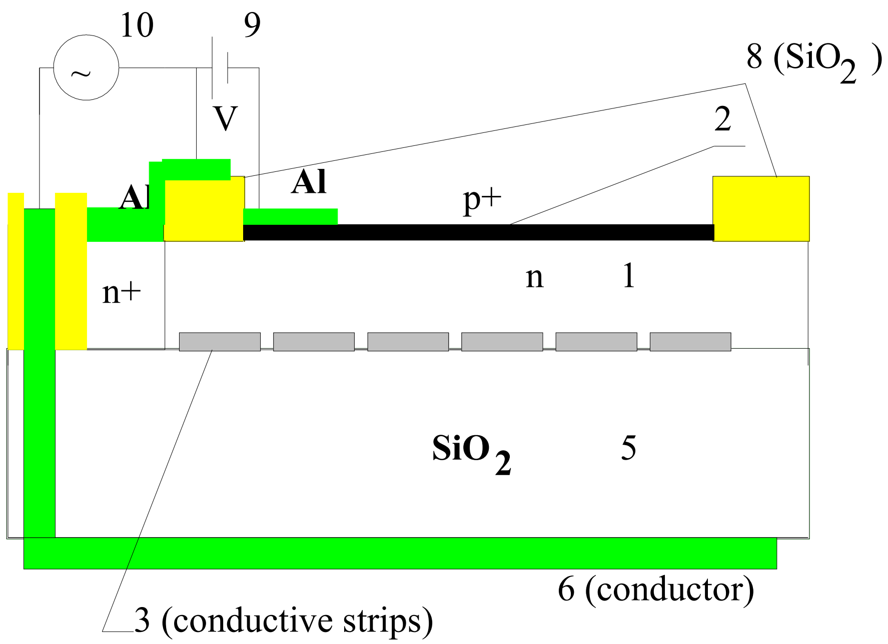

Fig.15. The MEA epiplanar capacitance transformer

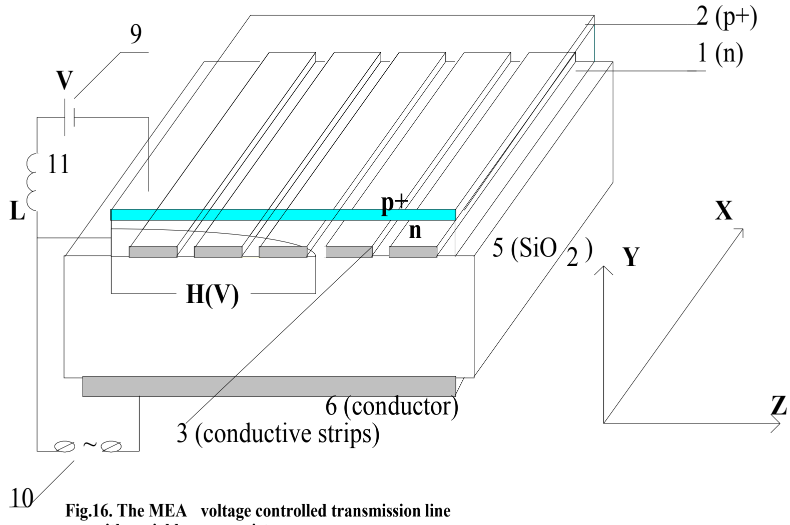

Fig.16. The MEA voltage controlled transmission line with variable wave resistance

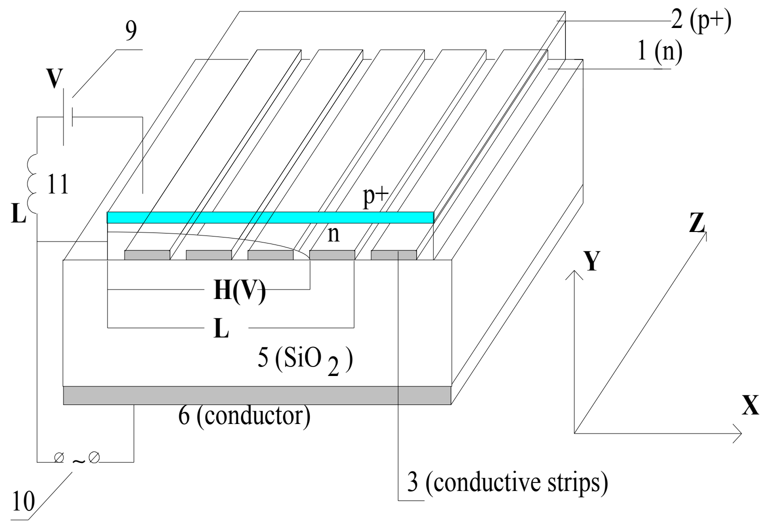

Fig.17. The MEA voltage controlled transmission line with variable length

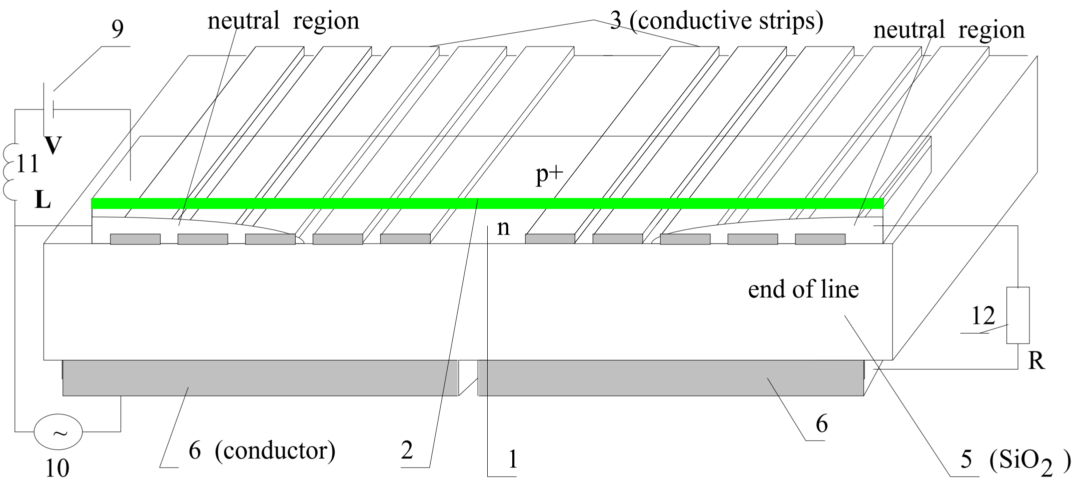

Fig.18. The MEA voltage controlled transmission line with variable wave resistance

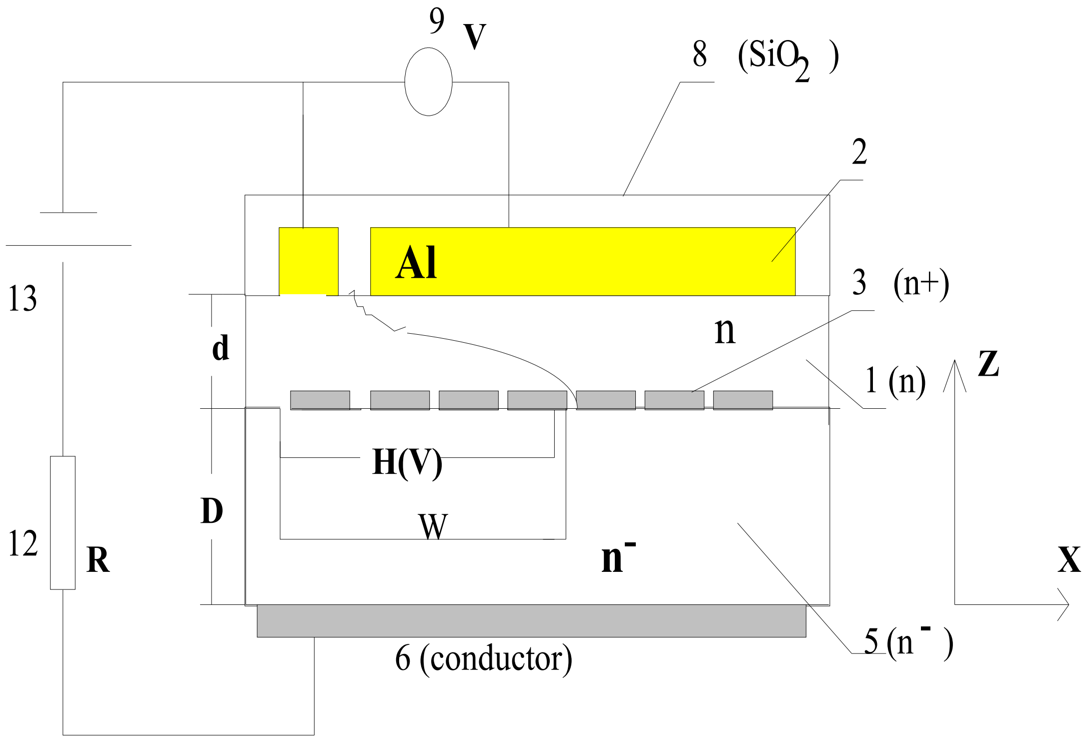

Fig.19. The MEA transistor

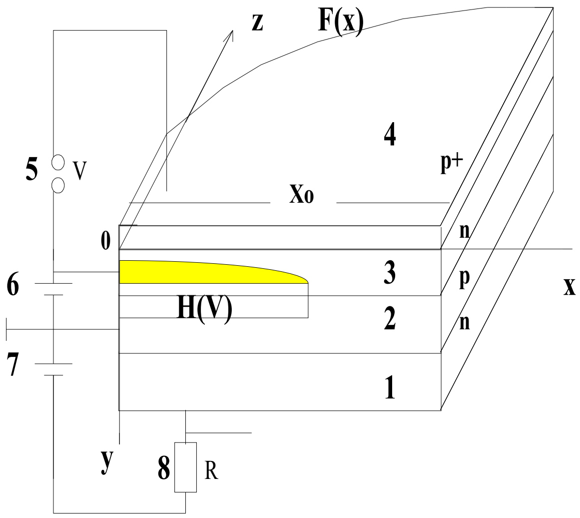

Fig.20. The MEA transistor amplifier

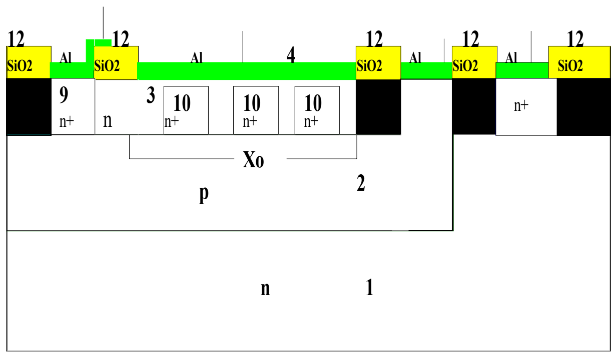

Fig.21. The MEA transistor with heavily doped strips in emitter

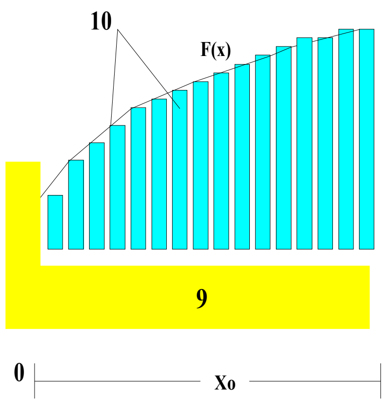

Fig.22. The emitter range view from the
controlectrode side