Resonant-frequency properties of low-dimensional junction of semiconductor-metal-semiconductor and calculation methodology

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Abstract. The article describes frequency characteristics of semiconductor–metal–semiconductor Si–Ag–Si structures (ohmic contacts) having metal nanolayers as well as features of resonance phenomenon and sandwich structure energy interaction. Mathematical simulation of mentioned above processes is provided. The limiting factor for resonance process is determined. It is found that the resonance frequency is a subject of semiconductor-metal junction parameters while metal layer thickness impact is minor.

1. Introduction
Small size of such sandwich structures provides a capability to use them as either a resonator or CL-element microelectronics or nano-electronics.

Meanwhile the structures of this type are not appropriate for the production of reactive elements, resonators and resonator-based circuits, passive frequency filters in microelectronics and/or nanoelectronics. Active filters are designed as integrated electronic components based on direct and back coupling operating amplifiers.

The issue is non-availability of microelements and nanoelements providing features of such components as reactive elements (inductance), resonators, frequency filters.

The results of a semiconductor-metal-semiconductor structure with an ultrathin metal layer investigation on amplitude-frequency properties are described hereby.

It is explained that the structure can be used in high-frequency and modulated signals processing as a frequency active element setting a fixed frequency (similar to a quartz resonator) as well as an element having LC characteristics.

2. Materials and methods
The following equipment was used for frequency characteristics analysis:
- Pulsed-oscillator Г5-56
- Oscilloscope С1-93
Connection diagrams are shown in the Figures 2 and 4. All the measurements are performed under normal conditions.

3. Results
The main feature of the structure is ultrathin metal layer (silver). Metal layers thicknesses in study samples are 0.7nm and 1.2nm. Semiconductor layers thicknesses (i-type silicon) are 70-80 nm. The energy band diagram is shown in Figure 1.

![Energy band diagram](image1)

**Figure 1.** Energy band diagram of semiconductor-metal-semiconductor structure.

**Figure 2.** Connection diagram for the study of the frequency characteristics of the structure.

![Connection diagram](image2)

**Figure 3.** Transients phenomena in the structure at a rectangular pulse.

Energy zones bending takes place at semiconductor areas while at metal areas it is not observed due to screening effect. The only role of ultrathin metal layers in the structure is metal-semiconductor contact formation resulting in the energy well appearance.
Upon an ohmic contact formation a number of electrons passes from metal areas into semiconductor areas creating enhanced regions. The enhanced regions are considered as an electron gas containing chaotically moving electrons able to pass through ultrathin metal layers since thicknesses of the metal layers are less than mean free path of electrons. For the electrons passing through a potential well with energy up to 5eV (in case of silver ultrathin metal layers) the mean free path is thought to be from 2.5 to 5 nm. [2]. In case of equilibrium, the number of electrons on one side of the contact is equal to the number of electrons on the other (in case of semiconductor layers of the same material). Once voltage is applied to one of the semiconductor regions, then the equilibrium is upset. Thus some electrons will pass through a thin metal layer to another semiconductor layer. Once the voltage is removed the electron gas returns to the state of equilibrium. This results in electron gas oscillations relative to equilibrium state (Langmuir oscillations of electrons) [3] (Figure 3).

The frequency of these oscillations depends on the total energy of the system and the type of potential well. In other words it depends on features of the ohmic contact

Figure 5 shows the amplitude-frequency characteristic of the Si-Ag-Si structure (80 nm-0.7nm-80 nm; 1-type silicon (undoped)). Resonance frequency for this structure is 8 MHz.

One-electron approach is used for frequency characteristics analysis due to low electron density.

In case of electron oscillation in a potential well $U(x)$ with oscillation limits $x_1$ and $x_2$, then the oscillation period is determined as follows [4]:

$$T(E) = \sqrt{2m} \int_{x_1}^{x_2} \frac{dx}{\sqrt{E-U(x)}}$$

where:

$m$ – electron mass;

$E$ – total electron energy;

Figure 4. Connection diagram for frequency characteristics analysis in case of free metal layer.

Figure 5. Amplitude-response curve for Si-Ag-Si structure (80 nm-0.7nm-80 nm).
$U(x)$ – potential electron energy;
Oscillation limits $x_1$ and $x_2$ are the roots for the equation $U(x) = E$

According to the research work [5], where $a$ is the characteristic length (the screening length – the limits of electron density change from $n_0$ (semiconductor intrinsic electron density) to $n_k$ (electron density at semiconductor-metal contact). In the general case, the width of the ohmic contact:

$$a = \left( \varepsilon k T \frac{1}{2 \pi n_k e^2} \right)^{1/2}$$  \hspace{1cm} (2)

where:
$\varepsilon$ – dielectric capacity;
$k$ – Boltzmann constant;
$T$ – Absolute temperature;
$e$ – Elementary charge;
n$_k$ - electron density at semiconductor-metal contact, which is determined by the following equation [3]

$$n_k \exp \left( \frac{e u_k}{k T} \right) = n_0$$  \hspace{1cm} (3)

where:
u$_k$ – contact potential.

According to the contact potential value $u_k$ is measured distantly from semiconductor-metal contact. It is used for calculations only and not shown in the figure. The contact potential is associated with the electron work function and in this case leads to energy structure formation [5].

Since metal layer thickness is much less than potential well width the metal layer shall be considered as entirely transparent to electrons. Thus we omit influence of the metal layer on electron gas oscillations.

Taking into account that $U(x)$ is symmetric about zero, the oscillation period is determined as follows:

$$T(E) = 2 \sqrt{2m} \int_0^{x_2} \frac{dx}{\sqrt{E - 2k T \ln \left(1 + \frac{x}{a}\right)}}$$  \hspace{1cm} (4)

For small-amplitude oscillations $x \ll a$, so:

$$\ln \left(1 + \frac{x}{a}\right) \approx \frac{x}{a}$$

Then [1]:

$$T(E) = 2 \sqrt{2m} \int_0^{x_2} \frac{dx}{\sqrt{E - 2k T \frac{x}{a}}}$$  \hspace{1cm} (5)
Taking into account that $U(x) = E$ we have the following equation for $x_2$:

$$x_2 = \frac{Ea}{2kT}.$$  

This results in the following oscillation period to electron energy function:

$$T(E) = 2\sqrt{\frac{2m}{\frac{Ea}{2kT}}} \int_0^{\frac{Ea}{2kT}} \frac{dx}{\sqrt{E - 2kT \left(\frac{x}{a}\right)^2}} = \frac{4}{3} \frac{\sqrt{2\pi m}}{2kT} \sqrt{E}$$  \hspace{1cm} (6)

In order to estimate applied voltage value influence on oscillation period and frequency it is necessary to take into account that the electron energy shall be defined as $E = e(\phi_1 - \phi_2)$ where: $\phi_1$ and $\phi_2$ are potential values at points $x_1$ and $x_2$, respectively.

$x_1$ and $x_2$ are turning points of electronic gas oscillation. The distance between them is much bigger than metal layer thickness. The screening length in the area of the ohmic contact is considered [4].

Upon electrons energy decrease (relaxation process is shown in selected region of Figure 3) frequency increases until electronic gas becomes stable.

The calculated maximum frequency value for Si-Ag-Si structure is 10 MHz in case undoped silicon is used ($n_k = 5.8 \times 10^{15} \text{ m}^{-3}$) as well as the thickness of the metal layer is 1nm. The calculated value is close to the experimentally obtained value (Figure 5).

The limiting oscillation frequency (period) shall be calculated with the condition that the electron oscillation energy is equal to thermal oscillation energy. It means (since one-dimensional case is considered):

$$T(E) = \frac{4}{6} \frac{\sqrt{2\pi m}}{e \sqrt{n_k}}$$  \hspace{1cm} (7)

Thus we have a mechanical resonance of aggregated electronic gas of enriched regions.

As resulted from formula (7) the maximum frequency of the structure is proportional to the electron density in the contact area. In case dopant concentration is increased up to $10^{15} - 10^{16} \text{ m}^{-3}$, the maximum frequency value will increase by $10^5$ and reach THz.

This reactive element has a certain resonant oscillation frequency. This frequency should be as high as possible, since the working area is below the resonant frequency.

4. Conclusion

Taking into account mentioned above data it can be concluded that the resonance frequency in the semiconductor-metal-semiconductor structure depends on ohmic contact characteristics (i.e. electron density in the enriched semiconductor-metal junction regions) and does not depend on metal layer dimensional characteristics (in this case metal layer thickness must be less than electron mean free path in current metal) [6].

Basing on the obtained results we can summarize as follows:
- to solve a number of problems in telecommunications it is proposed to use HTS elements as high-frequency filters (high-temperature superconductors). Their use is limited by maximum application temperature (70 K) and crock of structure (planar film structure with ring resonators using small surface areas) [7, 8].

Use of SMS-structure resonators provides the following capabilities:
- filtering of any spectrum signals;
- structure micro-size;
- operating at normal conditions (room temperature);
- at the same time, SMS structure considered as a microelectronics and/or nanoelectronics element can be used for manufacturing of nonlinear filters [9], ADSL filters [10], correlation filters [11], matched filters (spectral filter) [12], band-pass filters [13, 14], analogue of the quartz resonator.

Nowadays such filters are used in:
- passive elements (R, L, C);
- operational amplifiers with feedback;
- integrated electronic components (multipliers, integrators, signal generators, etc.).

The implementation of mentioned above devices allows:
- to use them as reactive elements in micro- and nanoelectronics;
- to simplify considerably designing of active and mixed filters;
- to reduce the cost of the final product [15, 16, 17].

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