Influence of Laser Fluence on Resistance Characteristics of Cobalt Ohmic Contacts Fabricated on Silicon Surface by Laser-Induced Diffusion

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Abstract

In this work, the influence of laser fluence on the resistance characteristics of cobalt Ohmic contacts produced on n-type silicon using laser-induced diffusion technique was introduced. A Q-switched Nd:YAG laser provided a quick, low-heat way to create a conductive $CoSi_2$ layer. The results show a direct link between the number of laser pulses and the contact's electrical performance with an optimum value of laser fluence that produces the lowest resistance. Initially, as the number of pulses increased, the sheet resistance dropped and conductivity improved. This is because the laser helped dopant atoms diffuse and become active, creating more free charge carriers. However, using too many pulses beyond a certain point caused the electrical properties to worsen, with the sheet resistance rising again. This degradation is due to the formation of crystal defects, which act as obstacles that slow down charge carriers.

Keywords: Laser-induced diffusion; Ohmic contacts; Cobalt dopants; Silicon devices

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1. Introduction

An Ohmic contact is a low-resistance, linear electrical connection between a metal and a semiconductor, essential for the efficient and reliable operation of electronic devices [1,2]. Unlike non-linear rectifying contacts, Ohmic contacts allow current to flow equally in both directions with minimal voltage drop. This is crucial for connecting components in integrated circuits, as high resistance at a junction would lead to excessive heat, signal degradation, and poor device performance [3,4]. The fabrication of these contacts involves meticulously cleaning the semiconductor surface, depositing a metal layer, and typically performing a high-temperature annealing process like rapid thermal annealing (RTA). This annealing step causes the metal and semiconductor to interdiffuse, forming a low-resistance alloy or silicide layer that facilitates charge carrier flow [5,6].

Laser-induced diffusion, also known as laser annealing, is an advanced technique for fabricating Ohmic contacts. It uses a high-energy laser pulse to rapidly and locally melt a very thin area of the semiconductor surface [7,8]. This process allows dopant atoms to diffuse into the semiconductor at extremely high concentrations [9]. The subsequent ultrafast cooling creates a heavily doped, high-quality crystalline layer that enables low-resistance tunneling of charge carriers, forming a superior Ohmic contact. This method is a low thermal budget process, meaning the surrounding wafer remains at or near room temperature, which is a major advantage for modern circuits with temperature-sensitive materials [10,11]. It also allows for the selective formation of contacts in specific areas and can achieve exceptionally low contact resistances, even on traditionally difficult materials like gallium nitride (GaN) and silicon carbide (SiC) [12].

Despite its benefits, laser-induced diffusion is not without its challenges. The rapid heating and cooling can induce thermal stress and crystallographic defects, such as dislocations, which can degrade device performance if not precisely controlled [13,14]. The process parameters—including laser energy density, pulse duration, and wavelength—must be carefully optimized for each material system to prevent surface damage [15]. Additionally, it can be more complex and costly than traditional methods. Nevertheless, recent research has demonstrated its immense potential, with successful applications in forming high-quality Ohmic contacts on materials for next-generation power electronics and UV LEDs [16,17].

In this work, the effect of varying laser fluence on the resistance of cobalt Ohmic contacts fabricated on n-type silicon substrates using laser-induced diffusion is presented.

2. Experimental Work

Preparing an n-type (111) silicon substrate for Ohmic contact experiments using laser-induced diffusion requires meticulous cleaning to ensure a pristine surface. The process typically begins with the removal of organic contaminants and native oxides.

A standard method for this is the RCA (Radio Corporation of America) clean, a two-step wet chemical process. The first step, SC-1 (Standard Clean 1), involves immersing the substrate in a solution of ammonium hydroxide (NH_4OH), hydrogen peroxide (H_2O_2), and deionized (DI) water at an elevated temperature, typically around 70-80°C. This solution effectively removes organic residues and particles from the surface. The substrate is then thoroughly rinsed with DI water. The second step, SC-2, uses a solution of hydrochloric acid (HCl), hydrogen peroxide (H_2O_2), and DI water, also at an elevated temperature. This step is crucial for removing metallic ions from the surface. Following another extensive DI water rinse, the substrate is ready for the final, critical step: removing the native oxide layer. This is accomplished by dipping the silicon wafer into a dilute solution of hydrofluoric acid (HF). This etches away the silicon dioxide, leaving a hydrogen-terminated surface that is less reactive and remains clean for a short period. The final rinse with DI water and subsequent nitrogen gas drying prepares a clean, oxide-free surface, which is essential for ensuring a direct, low-resistance interface between the metal contact and the silicon.

After the initial cleaning, the substrate is ready for the deposition of the metal and dopant layers required for laser-induced diffusion. The 1.5x1.5 cm dimensions are suitable for laboratory-scale experiments. The cleaned wafer is immediately transferred to a high-vacuum deposition chamber to prevent re-oxidation. A thin layer of cobalt is deposited using sputtering technique. This metal layer serves as both the contact material and a medium for the dopant atoms to diffuse into the silicon. Often, a thin layer of a dopant-rich material is deposited alongside the metal or as a separate layer. The thickness of the deposited layer is critical and typically in the range of a few nanometers to tens of nanometers. The wafer is then placed on a stage where it can be irradiated by the laser. A pulsed frequency-doubled Nd:YAG laser is directed at the specific areas where Ohmic contacts are desired. The laser parameters—laser fluence), pulse duration, and number of pulses—are carefully tuned to melt only the deposited films and a shallow, localized region of the silicon. This controlled melting allows the dopant atoms to rapidly diffuse and activate within the silicon lattice. The rapid solidification, in milliseconds, "freezes" the dopant atoms in place, creating a highly doped, low-resistance layer that forms the Ohmic contact. The localized nature of the laser annealing ensures that the bulk properties of the silicon substrate remain unaffected.

A Q-switched Nd:YAG laser system shown in Fig. (1) was used for fabricating Ohmic contacts on silicon substrates via laser-induced diffusion due to its ability to deliver high-energy pulses in a very short duration. The wavelength is a critical parameter, with the fundamental wavelength typically being 1064 nm, which silicon can absorb efficiently. The pulse duration is in the nanosecond range, usually between 5 to 10 ns. This short pulse width allows for rapid, localized heating of the surface, causing melting and dopant diffusion without significant heat transfer to the bulk of the silicon substrate. The laser fluence (energy per unit area) is a key parameter that must be carefully controlled to achieve optimal results. In this work, fluences range from 0.5 to 6 J/cm², and finding the correct value is crucial; too low, and the surface won't melt sufficiently for diffusion; too high, and it can cause ablation, thermal stress, and defects like cracks. Finally, the repetition rate (the number of pulses per second) and the number of pulses applied to a single spot are also important for controlling the overall thermal budget and dopant concentration at the interface.

Fig. (1) The Q-switched Nd:YAG laser system used in this work

3. Results and Discussion

Figure (1) shows the sheet resistance of a cobalt Ohmic contact on an n-type silicon substrate as a function of the number of laser pulses for three different laser fluences (0.5, 2, and 6 J/cm^2). This figure clearly demonstrates that both the number of laser pulses and the laser fluence are critical parameters for achieving a low-resistance contact. At all three fluences, the sheet resistance initially decreases rapidly as the number of laser pulses increases. This initial drop is a result of the laser-induced diffusion process, where each pulse provides localized, intense heat that melts a thin layer of the cobalt and the silicon substrate. This allows cobalt atoms to diffuse into the silicon lattice and react with it to form a conductive cobalt silicide ($CoSi_2$) layer.

The increasing number of pulses facilitates more complete diffusion and the formation of a more uniform and continuous silicide layer, leading to a higher concentration of dopant atoms in the silicon and, consequently, a lower sheet resistance. This is particularly evident for the fluence of 2 J/cm^2, which shows the most significant initial drop and reaches the lowest overall sheet resistance. However, this figure also shows a critical trend: the sheet resistance eventually plateaus or begins to rise after a certain number of pulses.

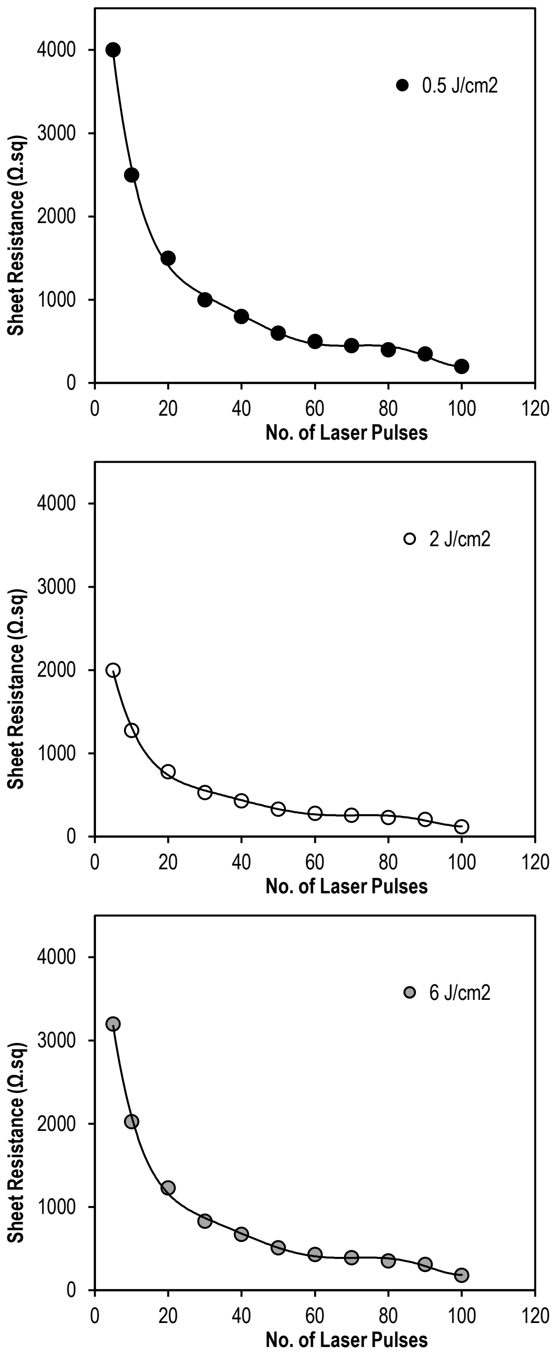

Fig. (2) Variation of sheet resistance of the treated samples with number of laser pulses for three different laser fluences

For the 2 J/cm^2 fluence, the resistance stabilizes at its lowest value around 80 pulses before showing a slight increase. For the 0.5 J/cm^2 and 6 J/cm^2 fluences, this trend is also apparent, though with higher final resistance values. This increase in sheet resistance with an excessive number of pulses is attributed to laser-induced damage. While the initial pulses are beneficial for silicide formation, too many pulses can lead to the formation of crystallographic defects, such as dislocations and cracks, in the silicon lattice. These defects act as scattering centers for charge carriers, reducing their mobility and causing the sheet resistance to increase. The graph highlights that an optimal balance must be struck to achieve the best contact performance. The 2 J/cm^2 fluence appears to be the most effective, as it provides sufficient energy for effective diffusion without causing the significant material damage seen at the higher 6 J/cm^2 fluence. The 0.5 J/cm^2 fluence, on the other hand, is likely too low to facilitate optimal diffusion, resulting in a consistently higher sheet resistance across all pulse counts compared to the 2 J/cm^2 fluence. The data confirms the importance of precise process control to achieve high-performance Ohmic contacts and avoids thermal damage.

4. Conclusions

In conclusion, laser-induced diffusion is a highly effective method for fabricating cobalt Ohmic contacts on n-type silicon. The process demonstrates a clear trade-off between the beneficial effects of dopant activation and the detrimental formation of crystallographic defects. While a certain number of laser pulses is necessary to achieve a low-resistance contact by forming cobalt silicide, exceeding an optimal pulse count can degrade performance by reducing carrier mobility. Therefore, meticulous control of laser parameters is essential to achieve a highly predictable, low-resistance Ohmic contact while avoiding device damage.

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